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# Effect of leaching on the strength properties of a hydrated lime-cement stabilized soil.

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Department:

# EFFECT OF LEACHING ON THE STRENGTH PROPERTIES OF A HYDRATED LIME-CEMENT STABILIZED SOIL

BY

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A

THESIS

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# INTRODUCTION

The stabilization of soil has been carried on since early historic times. The Romans used lime and volcanic ash as additives for this purpose. After the discovery of cement and its property of bonding soil particles it became one of the essential additives in the soil stabilization field. Many other kinds of additives have been developed and are being used today for soil stabilization.

A question that arises through the increasing use of stabilizers in soil is whether the changes that are effected are of a temporary or permanent nature. Changes may occur from the degradation of the stabilized soil by climatic changes, moisture movement and others. Among these changes the leaching by water associated with moisture movement can be considered one of the most influential one. The purpose of this investigation is to determine experimentally the effect of leaching, caused by the movement of water through the soil, on the strength characteristic of a soil stabilized by lime and cement additives.

The water penetrating the stabilized soil dissolves a certain portion of the lime. The amount of water and its flow speed in the soil depends upon the existing hydraulic water pressure gradient between the soil layers. The dissolved lime in the stabilized soil is taken away by the water at a rate determined by the above mentioned pressure gradient. Some cement particles may also be carried away by this water. As the result of this removal of lime and cement a detrimental change in the strength of stabilized soil might be expected.

Under highways and foundations it takes a long time for soil to be leached by water. In order to obtain the results of leaching action in a

reasonable time in the laboratory the electro-osmosis apparatus was considered as a possible method to force leaching action to expedite the experiments. The only difference between the use of this apparatus and the phenomena of leaching that occurs in soil in nature, is that in the former case $Ca^{++}$ ions of the calcium hydroxide are replaced by the ion particles from the anode during the ion migration whereas, in the later case, this does not happen. The reason for not using the electro-osmosis method in this experiment was that the method takes a long time and it is not definite as to what effect the ions emitted from the anode will have on the strength characteristics of the specimen. The method of leaching selected for use was a wetting and drying action further described under test procedures.

Since the nature of this investigation is more qualitative than quantitative, the results obtained in our experiment are not expected to be exact and hence the results can be considered within the range of natural acceptance.

For this experiment three sets of specimens were prepared each having two, four and six percent of lime. Each set contained four types of specimens having a cement range between 0 and 6 percent increasing by two percent increments. For all lime and cement combinations eight specimens were prepared to use in the triaxial test. Four of these specimens were tested at 0 and 60 pounds per square inch lateral pressure before leaching and the other four specimens were tested at 0 and 60 pounds per square inch lateral pressure after leaching.

To observe the change in the strength of various specimens the results found were compared for each individual lime-cement combination as well as the sets.

# REVIEW OF LITERATURE

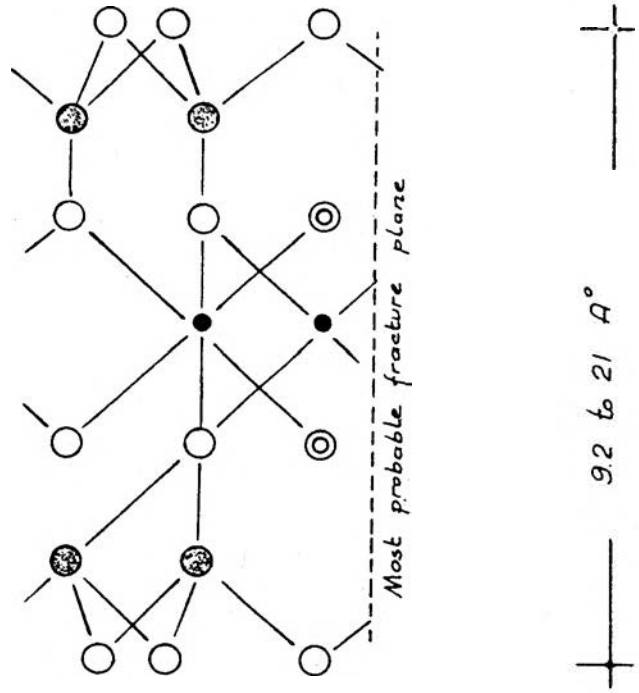
Civil engineers are frequently faced with the problem of building a structure through a clay material, as in the case of a tunnel in clay material; on a clay as in the foundation of a building; or with a clay material, as in the subgrade of a highway or an earth-filled dam. The method or the procedure, of necessity, is to obtain samples of the material which must be used, or is available, and to test them in the laboratory under conditions representing field conditions as nearly as possible. On the basis of the laboratory data, the engineer arrives at the structural design and, in so doing, frequently must predict how the soil material will act when it is placed under different conditions, for example, when the water table is changed, after a base-exchange reaction has taken place in the clay, etc. (1).

No existing literature is available concerning the effect of leaching on stabilized soils although the question appears to be pertinent to the overall life to be expected from such material.

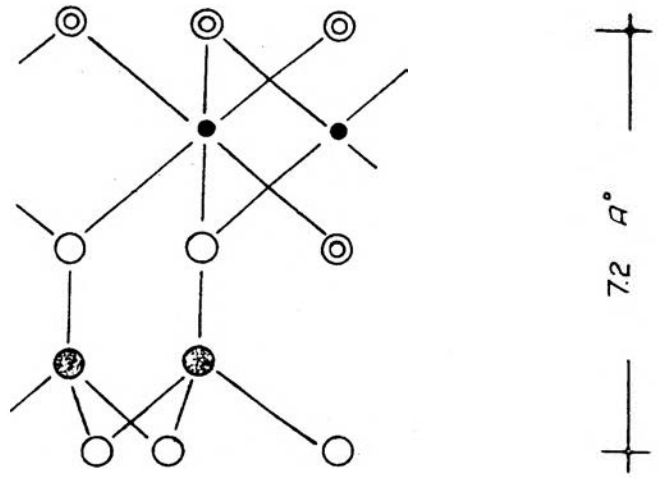
The following review of material which is predominantly concerned with clay-water systems is pertinent to the problem since it is largely this portion of the soil which is affected by stabilization with lime and cement as combined additives.

Numerous experimental findings have shown that the chemical and physical properties of soil are dependent upon the surface activity of the clay fraction. It has been adequately demonstrated that sand and silt possess little surface activity and, therefore, do not contribute much to many of the physical-chemical characteristics of soils. This small

(1) All references are in the bibliography.




(a)




(b)

Oxygen

Hydroxyl

Aluminum

Silicon

$A^{\circ}$ = Angstrom Unit
= $10^{-8}$ cm.

Figure 1. Lattice Structures of

a) Montmorillonite b) Kaolin .

Seat of ion exchange capacity

surface activity is due not only to a relatively low specific surface but also to the chemical and mineralogical nature of these coarser separates; that is, they are primarily quartz or unweathered primary minerals. Owing to the absence of any marked physical or chemical activity, the silt and sand fractions may be considered as the skeleton of the soil. The clay and the humus material are the active portions because of their high specific surface and their chemical constitution. Thus sandy soils are not physically and chemically active because of the large amount of skeleton material. Clays, on the other hand, are known to be plastic and sticky when wet, to shrink on drying, and to swell on wetting; they are poorly aerated and impervious to water. These pronounced physical properties result from the great surface activity of the colloid particles. (2)

All clay minerals adsorb positive cations by virtue of the unsaturated negative ions in the surface layers. In addition, montmorillonites, and to a lesser extent, some finely grained illites adsorb cations because they have charge deficiency within the lattice. These cations are held by only weak electrical forces and are easily replaceable by others.

The action of water on clay appears to be simple; if only a little water is present, the particles of the clay adhere together well and the solid mass increases in deformability highly in proportion to the water present. If a large excess of water is added, the particles of clay are separated from each other and again their behavior appears to be easily understood but, on investigating the matter still further, it is found that clays are the only natural minerals that possess, in so high a degree, the properties of plasticity.

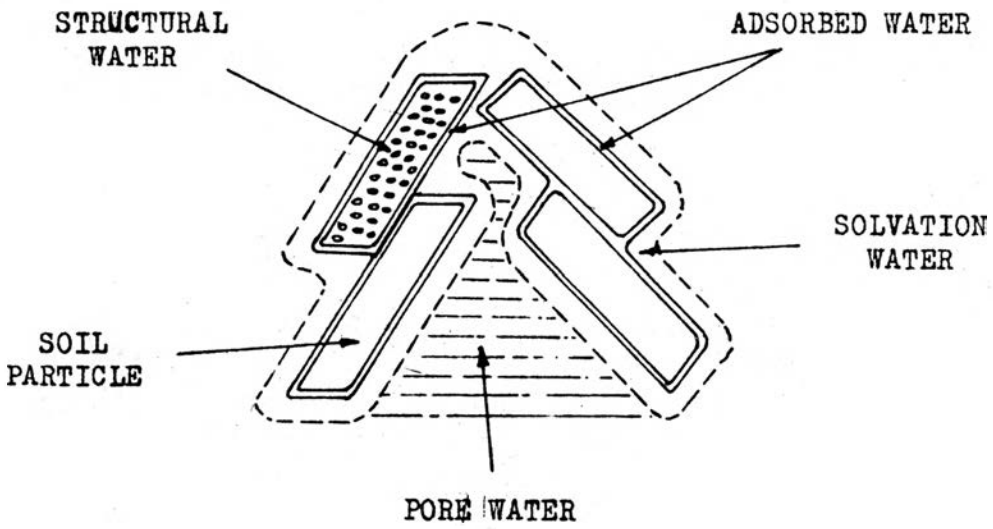



Figure 2. "Types" of the water in a wet soil -- Schematic

When clays are mixed with water, the properties of the resulting suspension are those of true colloid and the study of clays from the standpoint of colloid chemistry has led to a more complete knowledge of their behavior.

Water is known to exist in many forms in clays and similar materials, but the boundaries of each form are not clearly defined and there is considerable overlapping. The principal types are as follows:

1. Pore Water: This water has all physical and chemical characteristics of normal liquid water. Such water is displaceable by normal hydrodynamic means, provided it is not present in sealed-off pores, or in pores so small that capillary forces holding the water are greater than available hydrodynamic forces.

2. Solvation Water: This water is present in relatively thin layers around individual solid particles, and is held by polar, electrostatic or ionic-hydration forces near the particle surfaces. The water in these layers (probably not over 200 molecules thick) may be considerably denser and more viscous than ordinary liquid water, but is nevertheless mobile.

3. Adsorbed Water: This water is present extremely thin (1 - 10 molecules) layers on both the exterior and interior (for expanding lattice minerals) surfaces. The forces holding these water molecules are extremely large, so that this layer is essentially immovable by hydrodynamic mechanisms.

4. Structural Water: This is essentially not water at all, but represents hydroxyl groups which are integral parts of the solid crystal lattice. This water cannot be removed except by high-temperature breakdown of the crystal structure.

The four types of soil water listed above are shown in Figure 2. All are very important in determining soil structures and properties,

and it is difficult to ascribe greater significance to the part played by anyone. It is likely, however, that changes in physical properties of soil brought about by changes in water content are due to variations in pore or solvation water. This assumption appears justifiable in light of the fact that adsorbed water and structural water are so tightly held by the soil solids that little change in the amount of these types present would be expected to occur during normal variations in temperature and humidity at the earth's surface. The relative importance of pore water and solvation water in a soil system is in the main determined by the mineral constituents of the soil and the particle size present (4).

Colloidal particles when suspended in the water are changed and are surrounded by a water shell. The molecules of water within this shell are rigidly held by the particle and have a different character and properties from those in the remainder of the dispersion medium. The water may also contain cations and anions which play an important part in determining the behavior of the colloidal solution. Because of the intimacy of the association of the solid particle with its hydrosphere, it is convenient to regard these colloidal micelles, as the basic units in colloidal solution. In the crystal structure of clays the essential components are large anions (negative-charged ions) of oxygen and hydroxyl units held together by much smaller cations (positive-charged ions).

A cleavage section of a kaolinite (Figure 1b) crystal will be along the basal plane, exposing layers of hydroxyl and oxygen units, although only weak bonds are broken in the process. Fracture across the plate of these layer minerals, however, breaks valency bonds between

the cationic and anionic components. As the negatively-charged ions are very much larger than the positively-charged ones, the former predominate in the external layer. The net result of this, and the fact that the hydroxyl units themselves are also adsorbed, is that the surface of the clay particles and related minerals is negatively charged when suspended in a water medium. Consequently, it will attract cations and as a direct result the surrounding regions of the water medium in the immediate vicinity of the particles will be rich in positively charged ions which counter balance the surface charge and maintain electrical neutrality. Helmholtz was the first who recognized this important principle, and he postulated that a rigid double-layer was formed in close proximity to the clay surface, as illustrated in Figure 3a. Although Helmholtz's theory was a logical deduction, there were many

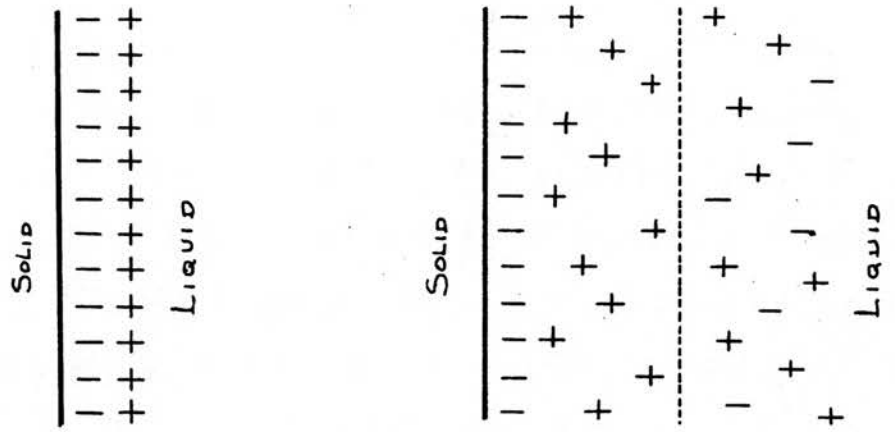



Figure 3

a. The Helmholtz Rigid Double Layer Theory

b. The Gouy-Freundlich Diffuse Double Layer Theory

shortcomings in the concept of a rigid monomolecular layer associated with the surface.

Gouy and Freundlich suggested that the layer of cations was not so sharply defined in thickness as Helmholtz supposed and introduced the diffuse double-layer theory. They maintain that the double layer is not limited to the layers of the hydrated shell in intimate contact with the surface, but extends some distance into the liquid medium. In other words, the counter-ions in the liquid are not statically held in close contact with the surface but are diffused throughout a definite volume of the liquid medium, as it is seen in Figure 3b. Gouy considers that the cationic distribution falls off exponentially as the distance from the surface increased. Thus a type of atmosphere is set up round the surface.

In the particular case of a clay suspended in water this ionic concentration gives rise to a secondary effect which limits the close approach of the cation to the surface of particles and gives rise to the diffuse double-layer. As a result of the intense electrical forces in the vicinity of the surface the molecules of the suspension medium are themselves oriented, giving rise to the layer or rigidly-held liquid. As the distance from the surface is increased, the degree of orientation of the molecules of the suspension medium decreases at the same rate as the concentration of counter-cations. The variation in these properties is a function of the surface and the type and concentration of the ions in solution.

Freundlich has investigated the electrokinetical laws which govern the variation in charge density at points extending outwards from the surface of charged particles and his conclusions are shown figuratively and graphically in Figure 4 in which the charges on the surface is regarded as 20e represented numerically by the point A on the ordinate with 0 as the point of zero change. Distances from the surface layer are

represented along the abcissa. The influence of the charged surface falls rapidly with separation distance to a zero point which represent the condition of charge in the suspension medium entirely removed from the influence of the surface. Two of the ways in which the potential drop may take place are shown in Figure 4B. In the first, the concen - tration of ions of opposite charge to the surface which are held in the

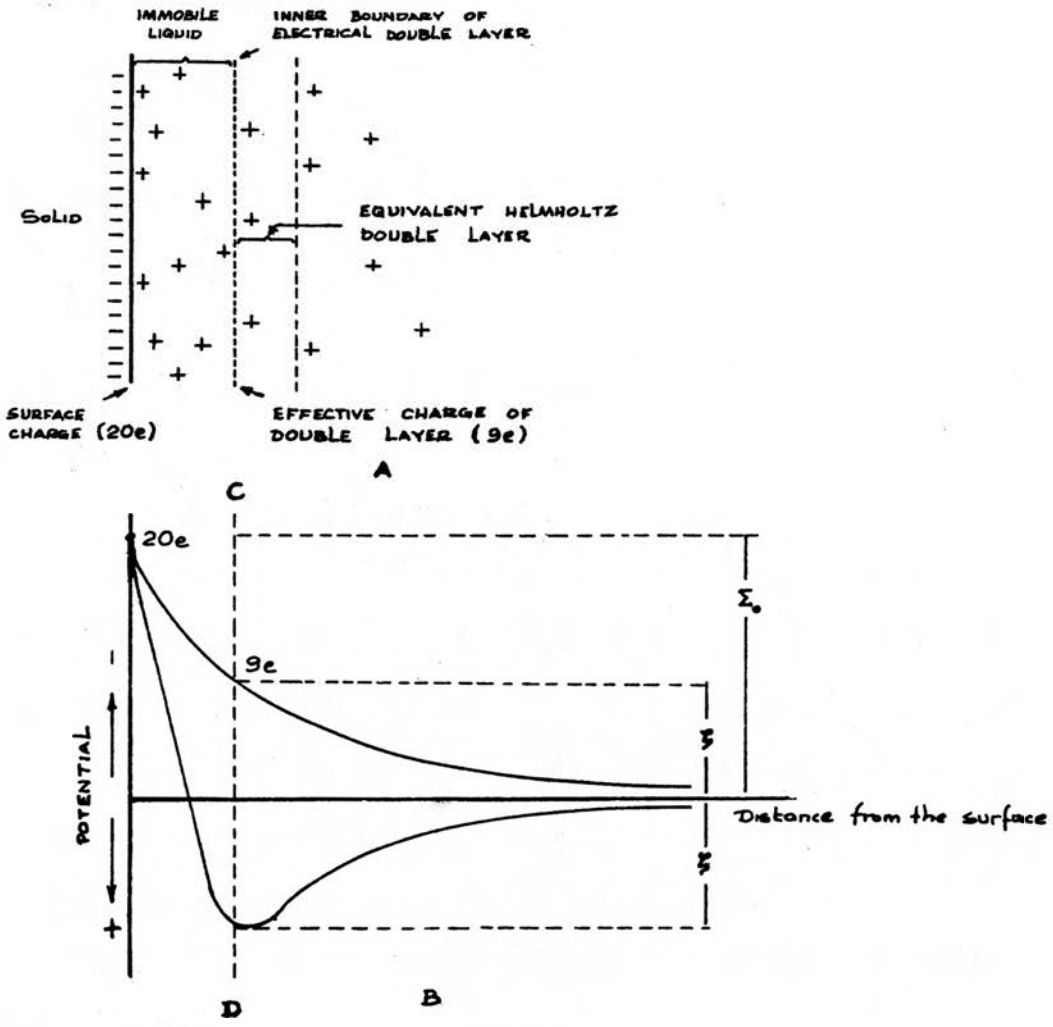



Figure 4. The Potential Energy Associated with a Charged surface

layer of rigidly-held water, is not sufficient to neutralize the charge which progressively falls to zero in the free water zone. In the second case, the ionic concentration in the oriented water layer is such that a reversal of charge takes place but, once again, there is a progressive decrease in the charge at distances outward from the surface. The edge (CD) of the rigidly-held water may be regarded as one plate of an imaginary condenser, the other being the point in the liquid where the charge has fallen to zero. Whereas Helmholtz imagined that this imaginary condenser was virtually a monomolecular layer thick, the Gouy-Freundlich conception

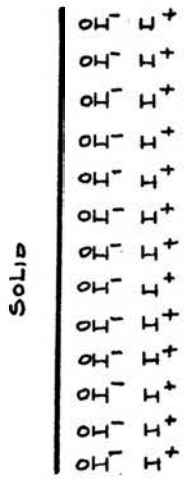



Figure 5. The Diffuse Double Layer when Hydrogen is the Counter-Balancing Cation.

is of a diffuse layer extending away from the surface. The electrokinetic potential of the 'condenser' or the Zeta- ( $\zeta$ ) -Potential, as it is known may be expressed simply by the relation derived by Muller and Abramson,

$$\zeta = \frac{4\pi e d}{D}$$

where e is the surface density of charge, d is the thickness of the layer, and D is the dielectric constant of the medium.

The zeta potential is a measure of the magnitude and extent of the forces arising as a result of the electrical charges on a particle. The surface density of charge (e) is a function of the type of surface and the ions which are present in solution.

Each colloidal micelle in a suspension will be surrounded by a hydrated shell and provided that the solid particles are of one type, each particle will have a charge of the same sign. Consequently, repulsive forces will be set up between all suspended particles, the magnitude and extent of which will depend on the zeta-potential. It is not surprising therefore, that many of the features of colloidal suspensions can be related to this value.

In the simplest case of a clay suspended in a pure water, negative hydroxyl ions will be adsorbed on the surface and the counter ions are the hydrogen ions ($H^+$) which make up the diffuse double-layer represented in Figure 5. As hydrogen ions are small, there can be little hydration, and few oriented water molecules to form a rigid layer. Conditions are favorable for the close approach to the surface of sufficient hydrogen ions to neutralize the charge; hence in a hydrogen clay suspended in pure water the hydrosphere surrounding the colloidal particles is small. In addition, the dielectric constant of pure water is relatively high, so that the zeta potential is low. In such a system the repulsive forces between the particles are very limited in extent, and individual particles can approach closely to each other without being repulsed. If the conditions in a colloidal system are such that the repulsive forces between the micelles operate at only small separation distances, the particles

may approach one another so closely that Van der Waal attraction forces become effective and cause aggregation and complete precipitation, i.e., flocculation.

The term flocculation implies the gathering of particles into 'flocks' which settle rapidly, leaving a clear liquid. Deflocculation is the reverse phenomenon, i.e., the dispersion of the aggregation into small particles which remain in permanent suspension.

The zeta potential is the factor which governs the stability of the suspension of clay particles. Tuoria has compared the case of flocculation with the zeta potential of kaolinite clay suspension.

By virtue of their negative surface charge, clay particles have the capacity to attract and adsorb positively-charged ions (cation) from the surrounding suspension. These cations are not firmly held and under certain conditions they can readily be substituted by others. This property is known as the base exchange capacity of the clay. The cation exchange capacity of clays is known to have a pronounced influence on their properties. The fertility of soils is partially dependent on the inorganic salts held in this way. In addition, a measurement of the cation exchange capacity may provide useful information to the ceramist as to the nature of the minerals in a clay. It may be determined (1) electrodialysis, or (2) by a chemical method.

The addition of cations to a colloidal clay suspended in water has a pronounced and important effect. Most cations are larger and more readily hydrated than hydrogen ions, therefore, if they are the counter ions in the clay micelle, the hydrated layer will be larger and the diffuse double layer increased as a consequence. The surface layer of the particles are capable of attracting a certain charge, hence it follows

that more monovalent cations can be influenced than divalent ones, which in turn will be more numerous than trivalent cations. Also, the larger the cation and the greater its degree of hydration, the more molecules of suspension medium are likely to be influenced and oriented; hence the more extensive will be the diffuse double layer and the repulsive force which is exerted by a particle on other particles in the immediate vicinity will be increased and will operate and be effective through a much greater distance.

The tendency of the different cations to be adsorbed is again predicted by a Hofmeister series. In general the greater the charge and the higher the atomic weight of the cation, the more readily will it be adsorbed, although hydrogen ion ($H^+$) takes preference over all others. The series is:

$$H^+ > Al^{3+} > Ba^{2+} > Sr^{2+} > Ca^{2+} > Mg^{2+} > NH_4^{1+} > K^{1+} > Na^{1+} > Li^{1+}$$

Therefore cations which would be valuable in increasing the zeta-potential and the degree of dispersion in a colloidal system are less readily adsorbed in to the hydrosphere of the micelle.

This difficulty can be surmounted by adding an excess of the required cation because the replacement reaction is an equilibrium process thus:

$$(clay^- - X^+) + Y^+ \rightleftharpoons (clay^- - Y^+) + X^+$$

where $X^+$ and $Y^+$ are any two different cations. Thus a sodium clay can be produced from a calcium clay by adding a sufficient excess of sodium ion and the amount of replacement is enhanced if at the same time the calcium ions can be removed from the system.

Monovalent cations such as potassium and sodium are large and highly hydrolysed. For a given charge on the adsorbing surface many more cations of this type can be attracted than (say) aluminum ($Al^{3+}$). For this reason and also because the number of oriented water molecules is much greater, the hydrosphere of particles with sodium or potassium as the counter cations is extremely large. The zeta potential of clays in the state is comparatively very large (Figure 6) and, consequently, the force of repulsion between particles is such as to produce maximum separation or, in other words, a deflocculated system (5).

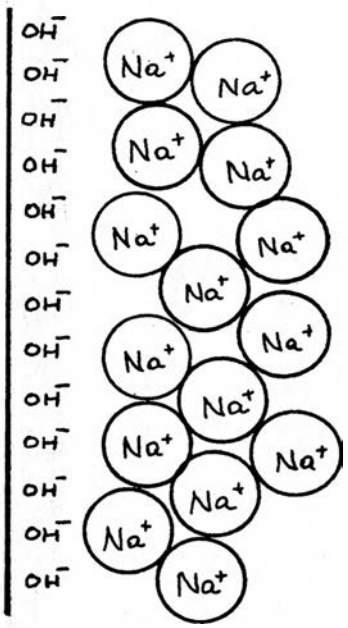



Figure 6. The Diffuse Double Layer when Sodium Ions are the Counter-Balancing Cations.

## MATERIALS

Materials used in this special research were soil, hydrated lime and cement.

Soil: All the soil used in this experiment was obtained from a farm owned by Mr. John Heagler, Sr. located about seven miles southeast of Rolla on Highway 72. The soil is from the B. horizon, and may be classified as a reddish yellow podzolic soil. The reason for selecting the soil from the B horizon is clearly stated by Mr. M. C. Spangler (8). He states "This lower horizon usually contains finer-grained materials and often is much more surface-chemically active and unstable than the soil above it or below it. These characteristics render the B horizon extremely important in highway and airfield design and construction or other work in which the foundations are located near the ground surface".

The specific gravity of the soil was determined in accordance with the Standard Method of Test for Specific Gravity of Soils, ASTM Designation: D854-52 (10), and was found to be 2.60.

A liquid limit test conducted in accordance with the tentative method of test for liquid limit of soils, ASTM Designation: D423-53T (11) and was found to be 35.5%.

The plastic limit was determined in accordance with the Tentative Method of Test for Plastic Limit and Plasticity Index of Soils, ASTM Designation: D424-54T (12) and was found to be 19.0%. Plasticity index = 35.5 - 19.00 = 16.5.

Grain soil analysis of the soil was performed in accordance with ASTM Designation: D422-54T (13) and the grain size accumulation chart was plotted in Figure 7. This soil, with eighty-six percent passing No. 200 sieve, a liquid limit of 35.5% and a plasticity index of 16.5, is

classified as A-6 by the American Association of State Highway Officials Classifications (14) and it is described as "a plastic clay soil usually having seventy-five percent or more passing the No. 200 sieve. Materials of this group leave a high volume change between wet and dry states. This group index values range from 1 to 16, with increasing values indicating the combined effect of increasing plasticity indices and decreasing percentages of coarse material".

The PCA Soil Primer (15) describes group A-6 soils as "soils possessing little internal moisture contents. These soils are not suitable for use as subgrades under thin flexible base courses or bituminous surfaces because of large volume changes that are caused by moisture changes, and the loss of bearing power after the entrance of moisture. The heavier A-6 soils may require insulating courses to prevent excessive concrete pavement distortion or mud-pumping. All flexible-type bases must have an insulating courses of A-1 or A-2, stone chips, etc., or soil cement to prevent the clay from working into the flexible base, thus destroying its load-carrying capacity".

Hydrated Lime: The hydrated lime used in this experiment was ordinary commercial grade, manufactured by Ash Grove Lime and Cement Company at Kansas City, Missouri.

Portland Cement: All cement used in this experiment was Type I Portland Cement manufactured by Ash Grove Lime and Cement Company at Kansas City, Missouri.

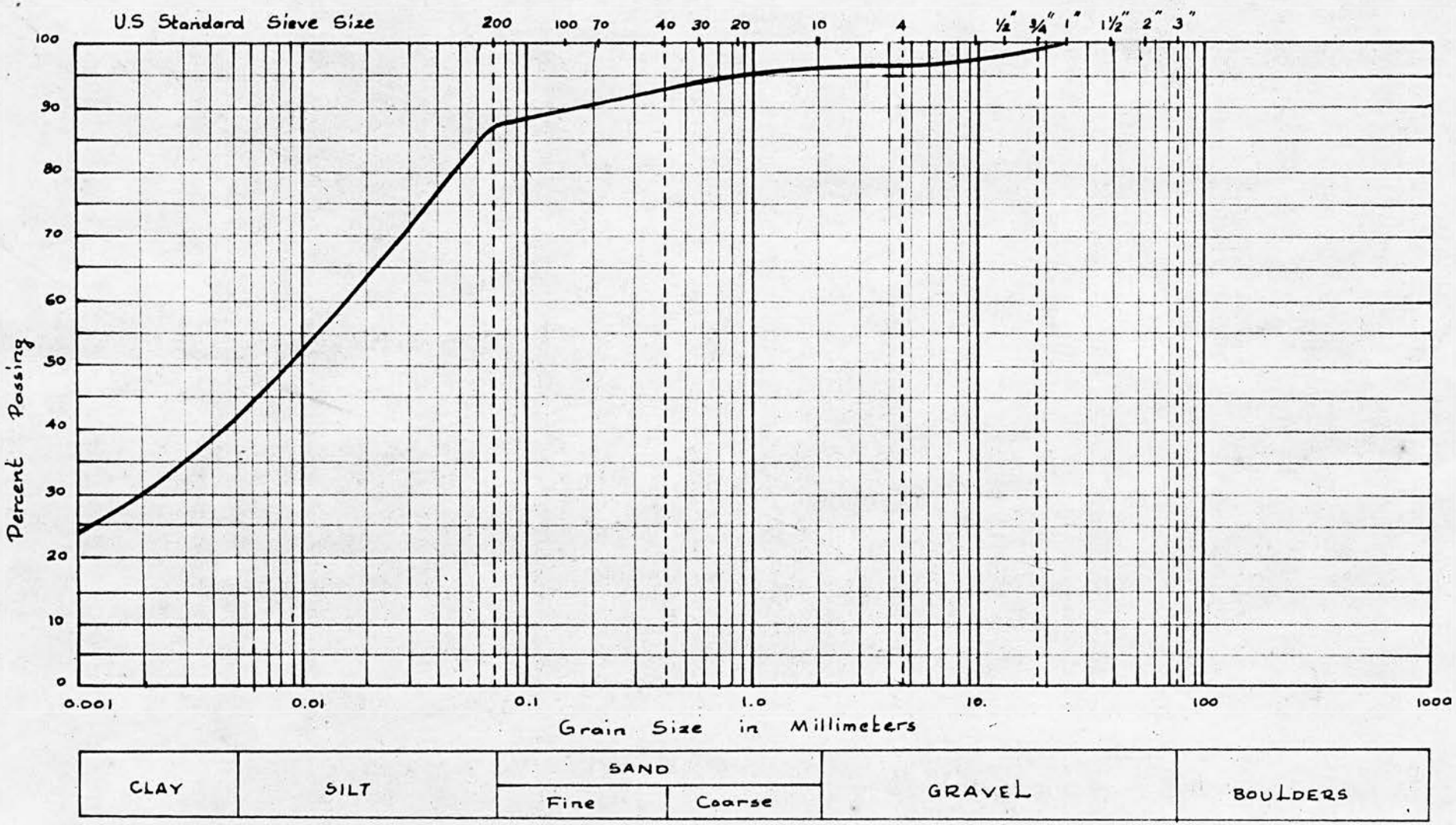



Figure 7. GRAIN SIZE ACCUMULATION CHART

## PREPARATION OF SPECIMENS

For the triaxial test the soil, which was taken seven miles from Rolla, was sieved using the U. S. Standard No. 10 sieve. The rest of the material on the sieve was discarded. Then the soil was oven dried under medium heat to keep the chemical character of the soil from changing. After being taken out of the oven the soil was mixed with the different amounts of cement and lime previously stated. All mixing was done in the Lancaster counter batch shown in Figure 8. During the mixing a certain amount of distilled water was added to the material to obtain a uniform mixture at optimum moisture content. Following the mixing the mixture was compacted into the Harvard miniature mold (B in Figure 9) in three layers and each layer was compacted 25 times with the hammer shown in Figure 9, labeled A. Using the other Harvard apparatus, which is seen in Figures 10, 11 and 12, the specimens were taken out of the miniature mold.

For this experiment three sets of specimens were prepared with two, four and six percent lime respectively. Each set contained four types of specimens having a cement range between 0 and 6 percent increasing by two percent increments. For all individual cement - lime combinations eight specimens were prepared with a height of 2.75" and a diameter of 1.25" for use in the triaxial test.

All of the prepared specimens were placed in the curing jar to be cured in moist air for seven days, Figure 13. Half of the specimens were removed from the curing jar at the end of four days of curing to begin the leaching process. For this purpose the specimens, taken out of the jar were immediately weighed and placed into the water bath, as is

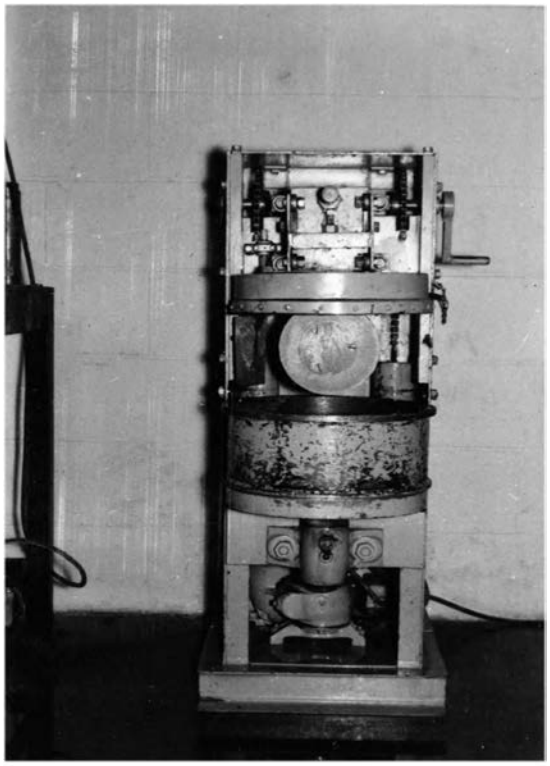


Figure 8 -- Lancaster Counter Batch Mixer

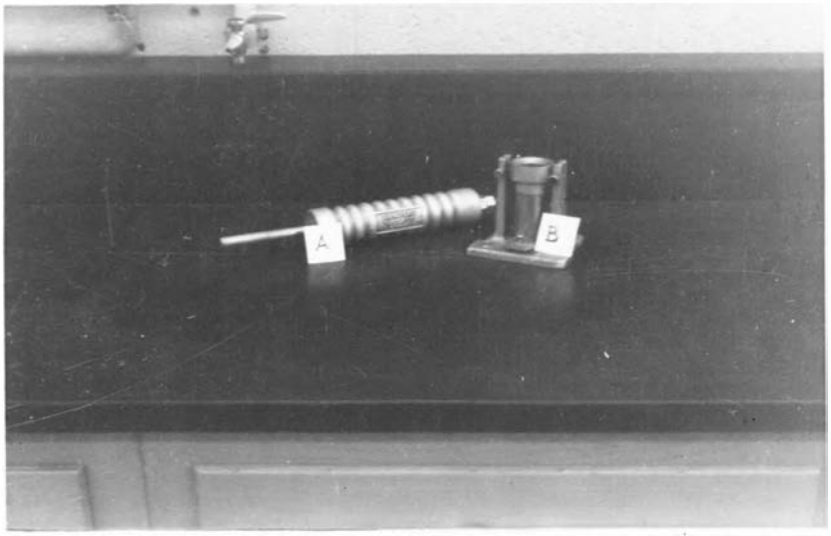



Figure 9 -- Compaction Hammer and Mold

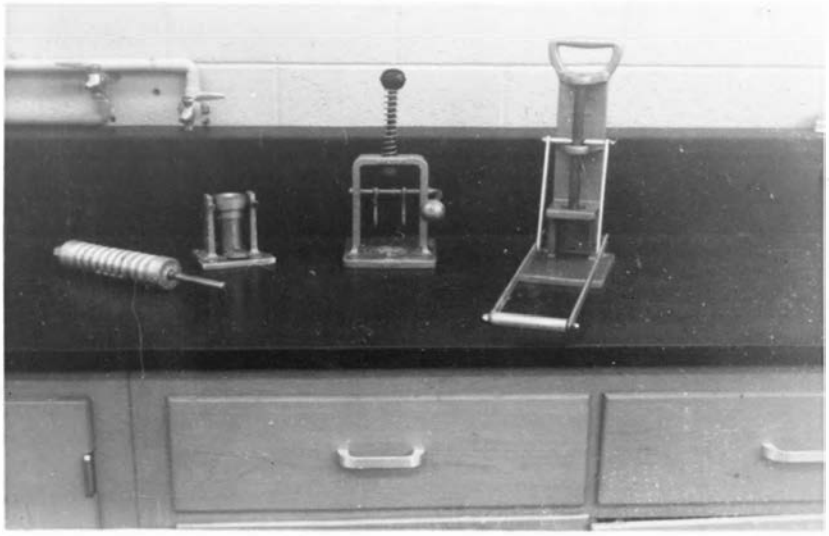



Figure 10 -- Complete Harvard Compaction Assemble

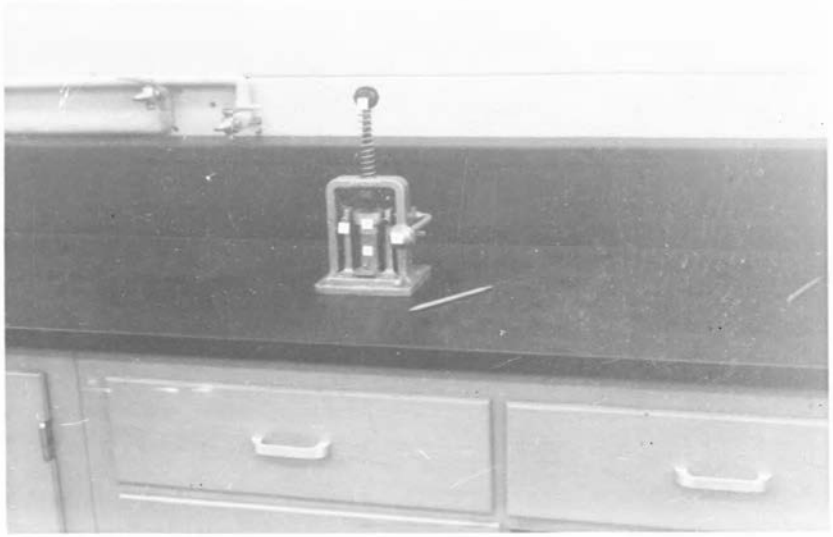


Figure 11. Harvard Extrusion Device

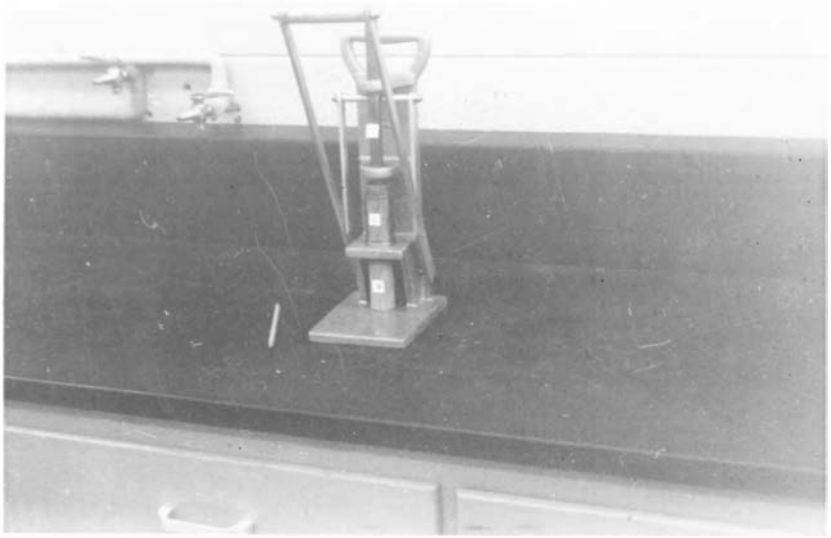



Figure 12. Harvard Extrusion Device

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Figure 13 -- Constant Humidity Curing Jar

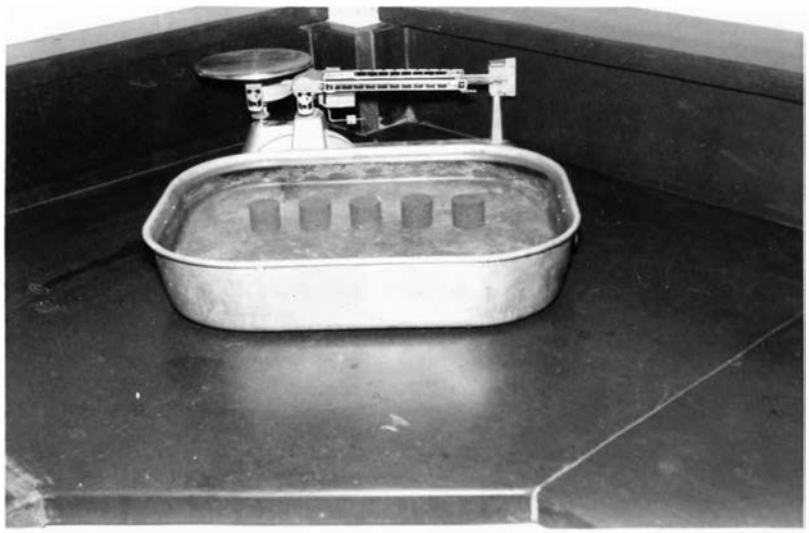

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Figure 14 -- Leaching of Specimens

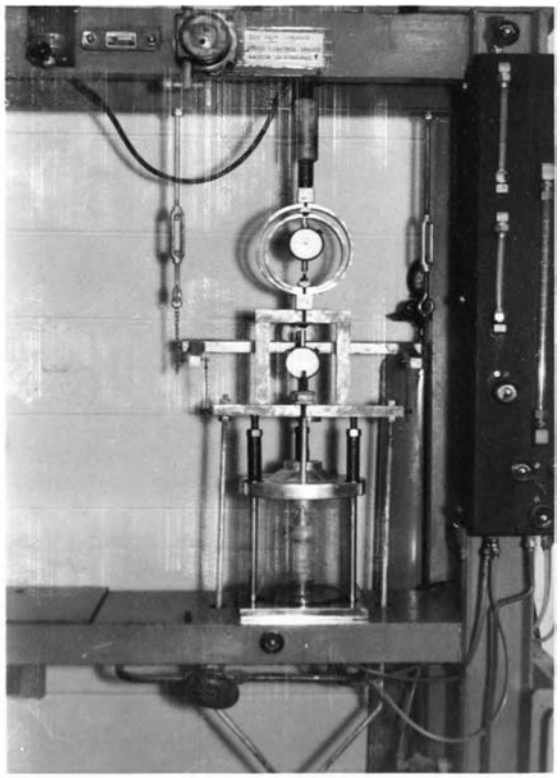

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Figure 15. Triaxial Test Machine

# Optimum Moisture Content Curve

Dry Density v.s. Moisture Content
Max. Dry Density = 102.25 lb/cu.ft.
Opt. Moisture Content = 20.25 %

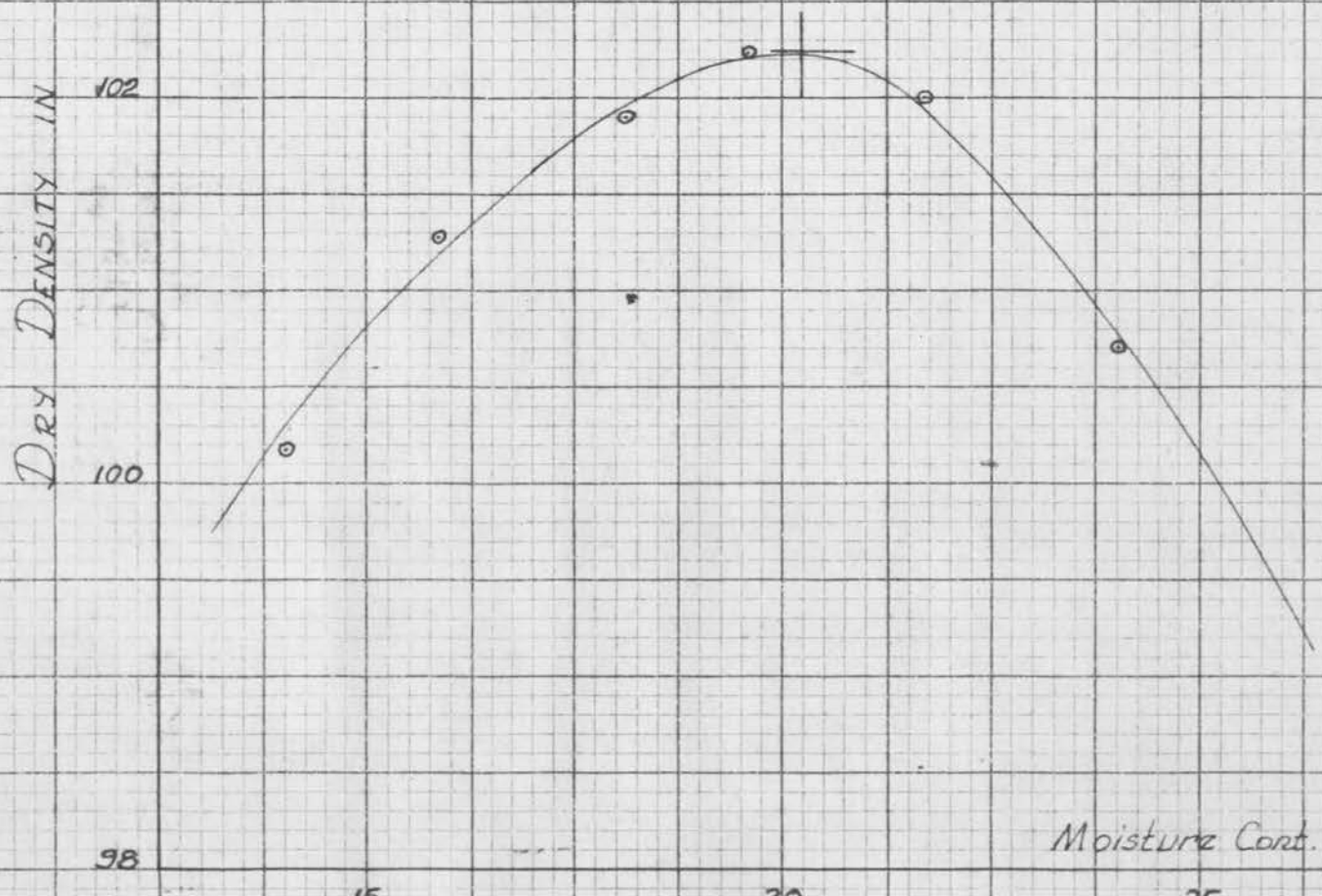


FIGURE 16. COMPACTION TEST ON SOIL

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Figure 17. Removed $Ca^{+}O$ Particles from the Leached Sample.

seen in Figure 14. During the leaching great care was taken to assure very accurate duplication of natural leaching condition. The specimens were left in the water for four hours. At the end of four hours the specimens were taken out of the water and immediately weighed and placed in the oven for four hours at the temperature of 80°C. During the heating the temperature was maintained constant at 80°C to prevent the soil from undergoing chemical change that might occur at higher temperature.

The same wetting and drying cycles of specimens was repeated five times which took a total of three days. At the end of the seven days all specimens were tested with the triaxial test machine. Both unleached and leached samples were tested at 0 and 60 pounds per square inch lateral pressure. For each lateral pressure two individual specimens were tested and the plotted stresses are the average of the ultimate stresses. During the leaching the first four specimens, which contained only two percent lime, disintegrated under the effect of leaching.

TRIAXIAL TEST

The triaxial test machine is shown in Figure 15. The cylindrical surface of the specimen was covered with the rubber membrane. The ends of the sample were placed on porous stone (for drainage). After setting up the triaxial apparatus, by tying the three 5/6" diameter stainless steel bars at a spacing of 120°, glycerin was used inside the cylinder and lateral pressure was applied to this fluid (60 psi). This pressure was held constant during the experiment. The stress and the strain gages were adjusted to a zero reading and the test was run at the deformation rate of 0.03 inch per minute (7) until specimen failed.

OPTIMUM MOISTURE AND DENSITY TESTS

For this test the Harvard Miniature mold was used. A sufficient amount of the soil passing the number 10 sieve was mixed with a sufficient amount of water, and then compacted in the cylinder in three equal layers, each layer being compacted by 25 blows. The compacted soil was carefully leveled off to the top of the cylinder with the straightedge, the outside of the cylinder cleaned of excess soil, and then weighed. After that the soil was removed from the mold and immediately a small amount of soil was taken from the center of the sample for moisture determination. The weighed and identified moisture sample was placed in the oven for drying. By addition of almost two percent water the process was repeated again. The test was repeated six times until two tests showed a decreasing total weight of the specimen. For this purpose the test was started with 14 percent of water. The laboratory dynamic compaction tests are presented in a plot of dry density versus water content. As it is seen in Figure 16, the smooth curve was drawn through the plotted points. From this curve maximum dry density and optimum moisture content were determined.

# DISCUSSION OF RESULTS

The purpose of this research was to investigate the effect of leaching on the strength of lime and cement stabilized soils. To understand the results of the tests it is necessary to understand the effect of these two materials on the clay soil when they are used as stabilizing agents.

When the calcium hydroxide is added to the soil water system the ion exchange discussed in the review of literature takes place with an accompanying decrease in the zeta potential. A flocculated system is thus formed which imparts to the soil system very definite physical characteristics. Goldschmidt and Lambe (3) have proposed that clay soil structure may exist as:

(1) Strongly flocculated (2) Mild flocculation (3) Dispersed

Each of the above systems will exhibit different characteristics under load with #1 having high friction and shearing strength, #2 medium friction and easily collapsed into condition 3 under load, and #3 having very low friction and possibly high cohesion depending upon the amount of water present in the soil.

The cement additive is required to increase the cohesion of the highly flocculent system to further improve the strength characteristics of the system and to improve the durability characteristics of the soil under freeze-thaw, wet-dry conditions. It has been previously noted in thesis study by Frankenberg (6) that lime stabilized soils do not hold up well under these strenuous durability tests.

The wet-dry durability tests are basically a leaching test as well as a slaking test which poses the question of "what happens when the lime-cement stabilized soil is exposed to this action?"

Leaching of a soil may take place due to a number of reasons. Rain water which is mildly acidic may remove the adsorbed cations by hydrogen replacement and solution ions present in the ground water may be exchanged with the adsorbed ions, in the diffuse layer. Organic acids in the soil may have the same effect as the mildly acid rain water.

The following specific results of the tests performed indicate that the effect of leaching on soil stabilized by both lime and cement is not without affect on the system but the effect is not large in magnitude nor extremely detrimental.

During the preparation of the specimens some of the physical changes were observed. The friability of the soil increased as the lime percentage was increased during the mixing. As it is observed from the moisture content curve and the tables (Figure 16 and Appendix A, Table 1) an increasing water content was needed for the compaction of the stabilized soil as the lime percentage increased. The optimum moisture content was 20.25% for the natural soil and 23.9 for 6% lime additive. Amount of cement added did not affect the optimum moisture content as noticeably. This showed that the increase of the water content was more related to the lime percentage than the cement. Also while the percentage of the lime-cement and the water content was increased, it was seen that there was a decrease in the dry density of the soil, (see Appendix A, Table 1). These changes were due to the flocculation of the clay particles in the soil and more open framework of a highly flocculated soil structure. During the alternate wetting and drying

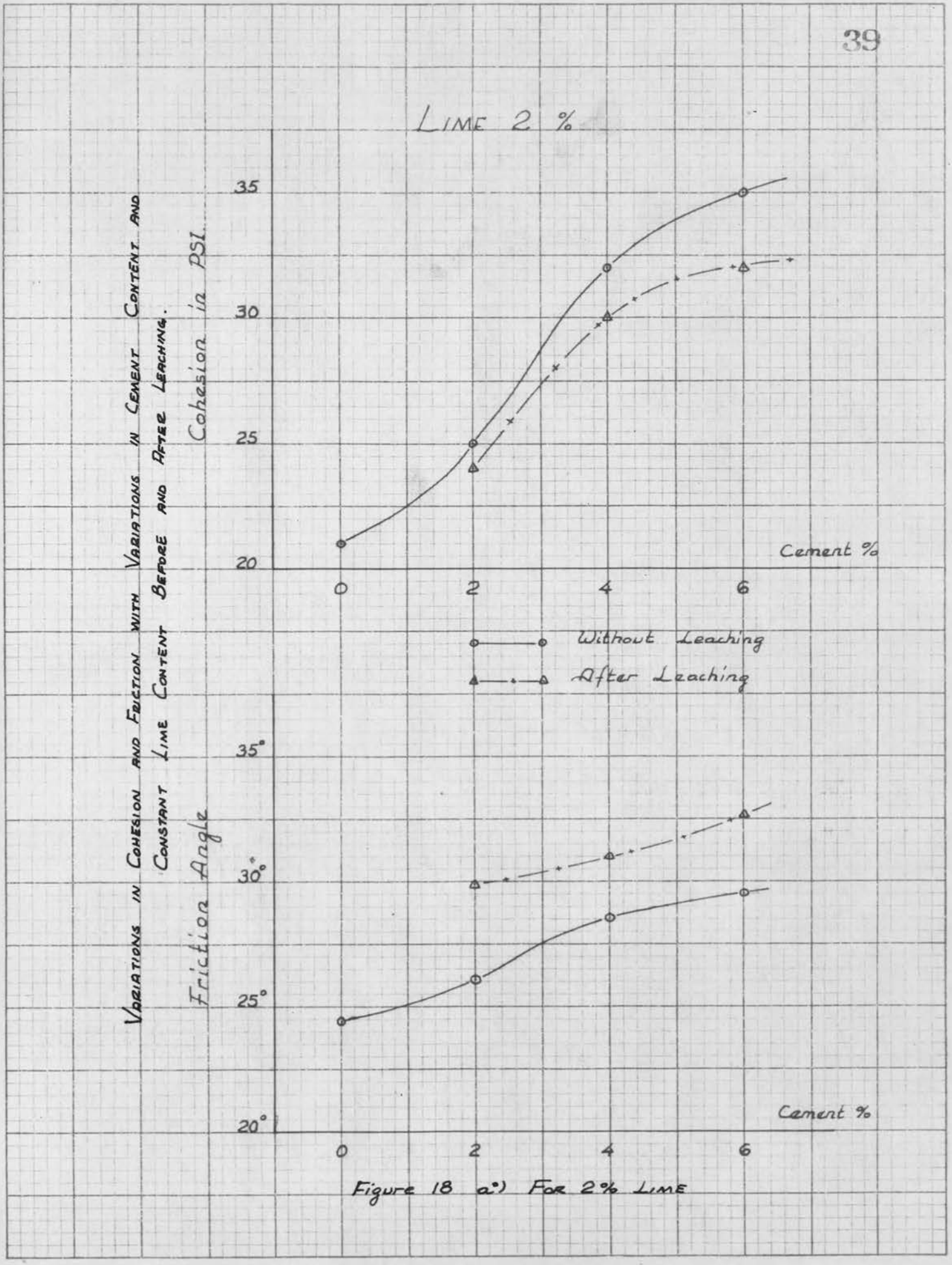
test at the end of the four hours it was observed that the soil lost 90 to 95 percent of its total water content which had been taken into the structure during the wetting and mixing, also color changes and the white $Ca^{++}$ particles were observed at the surface of the specimens after being taken out of the oven. This was the evidence that lime was being removed under the effect of the water.

Appendix B, Table 2, shows the results of the compressive strength tests on the control specimens and the leached samples. Appendix C, Table 3, shows the values of the friction angle and cohesion before and after the leaching process as determined from the Mohr's Circles which are shown in the Appendix D. Figure 18 a, b and c was plotted from the values of Table 3.

As can be observed from the Mohr Circles and rupture envelopes both cohesion and angle of friction increase with increasing percentages of lime and cement in the control specimens. This indicates that there is an increase in the degree of flocculation and the bonding of the particles with an increase in the amount of additives. After leaching the results indicate that there is a loss of cohesion with an accompanying increase in friction.

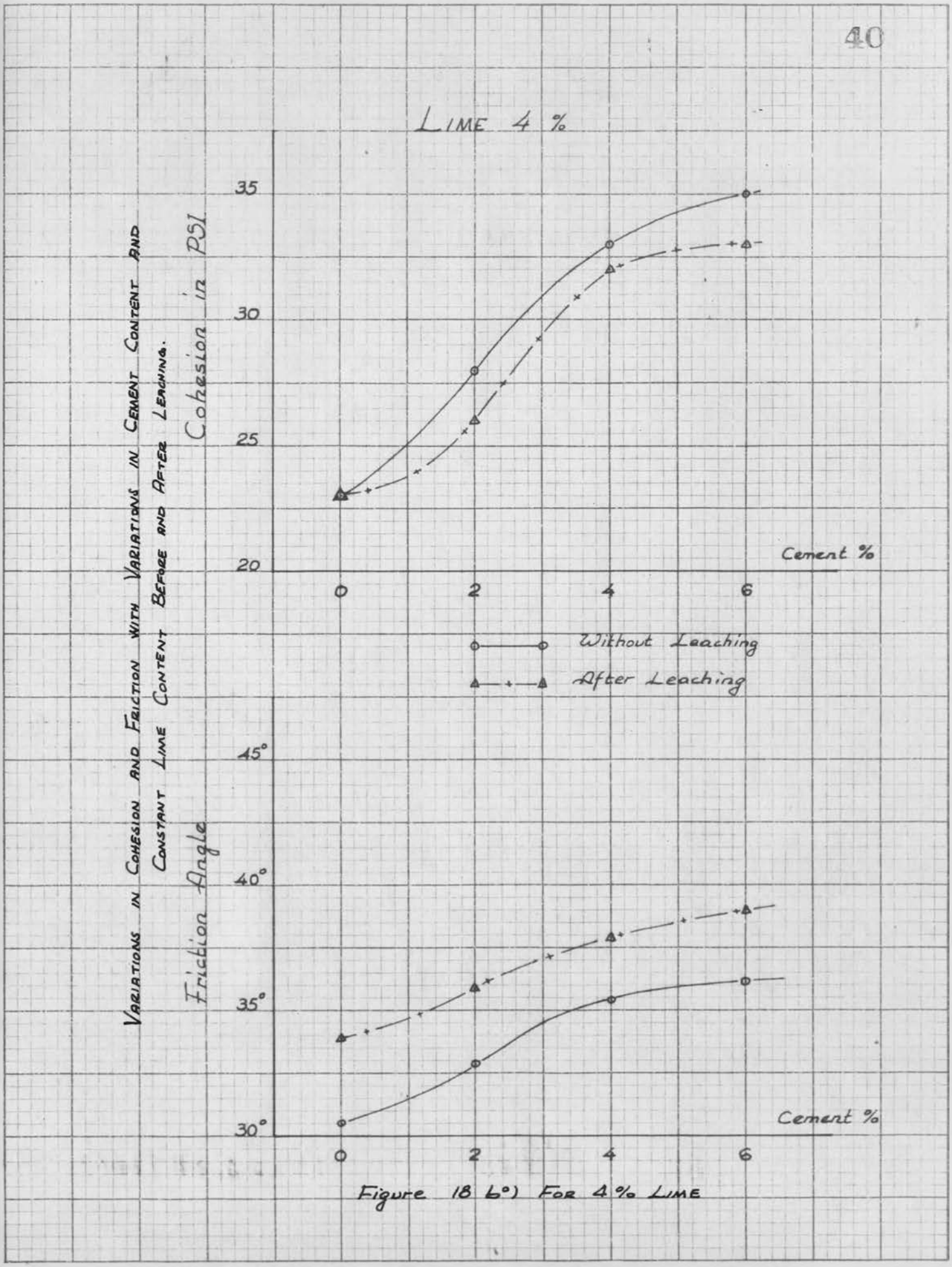
Figure 18 a, b and c further indicates that the cohesion loss in the leached samples increases, relative to the cohesion of the unleached samples, as the percent cement is increased for each percent of lime. The increase in the angle of friction upon leaching appears to diminish relative to the unleached samples as the cement content increases.

From the theoretical viewpoint of the investigation, the increase in the compressive strength can be related to the particles which go into reaction under the effect of water. The soil used in this investigation,



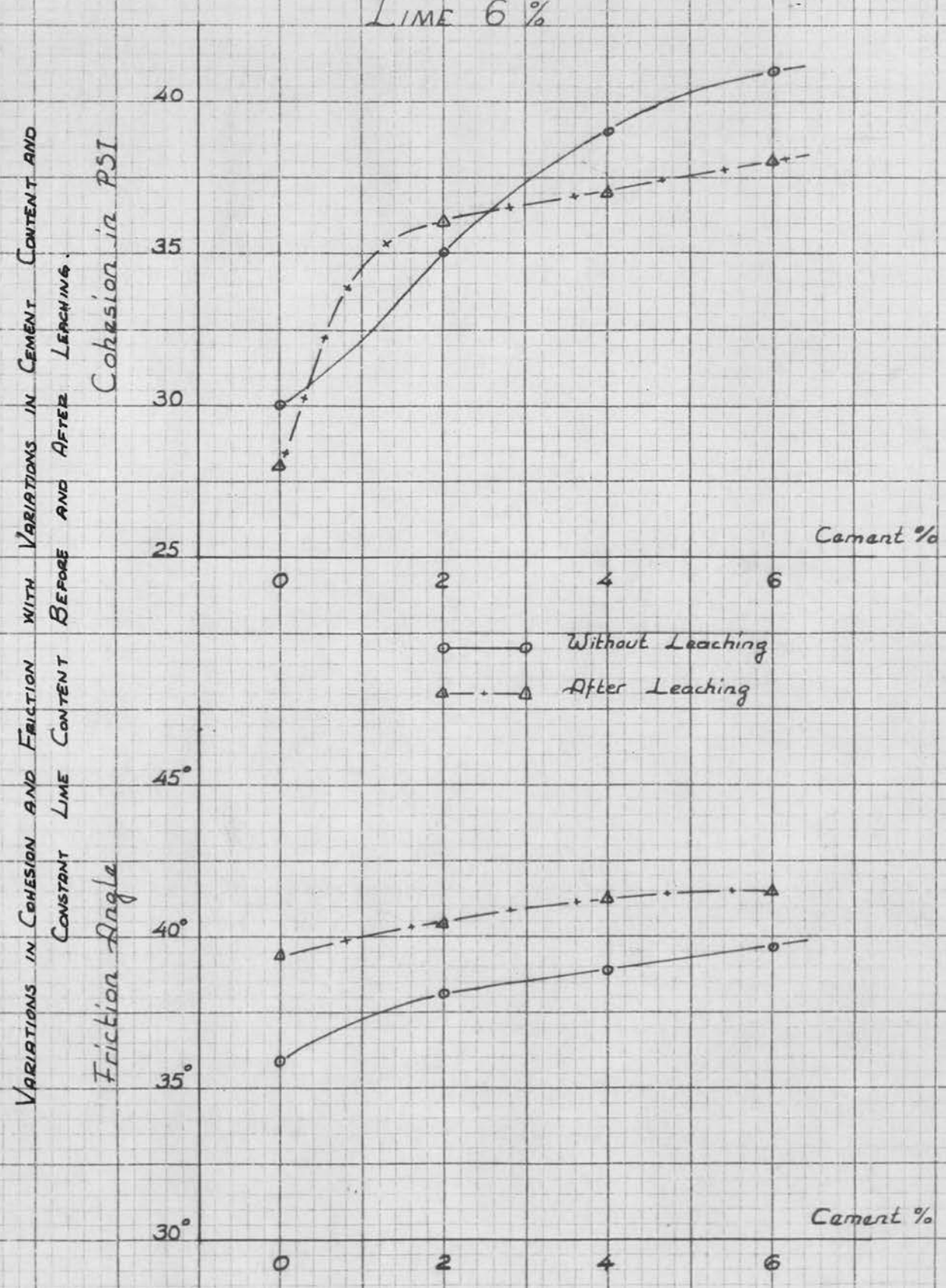

VARIATIONS IN COHESION AND FRICTION WITH VARIATIONS IN CEMENT CONTENT AND CONSTANT LIME CONTENT BEFORE AND AFTER LEACHING.

Figure 18 a°) FOR 2% LIME




VARIATIONS IN COHESION AND FRICTION WITH VARIATIONS IN CEMENT CONTENT AND CONSTANT LIME CONTENT BEFORE AND AFTER LEACHING.

Figure 18 b) FOR 4% LIME




VARIATIONS IN COHESION AND FRICTION WITH VARIATIONS IN CEMENT CONTENT AND CONSTANT LIME CONTENT BEFORE AND AFTER LEACHING.

Figure 18 c°) FOR 6 % LIME

which was stabilized with lime and cement, primarily has $Ca^{++}$ ions at the surface of the colloidal clay particles. It has been proposed that the effect of the water, in the diffuse layer of a colloidal micelle $Ca^{++}$ ions are replaced by $H^{+}$ ions. (The valance of hydrogen is one). But actually, the volume of the hydrogen ion is comparatively smaller than the calcium ions. This caused a decrease in the thickness of the diffuse layer of the colloidal micelle as it was shown in Figure 19.

Since the thickness of the diffuse layer is directly proportional to the zeta ( $\zeta$ ) potential, this decreases the zeta potential (5).

$$\zeta = \frac{4\pi e d}{D} \qquad \zeta' = \frac{4\pi e d'}{D}$$

$$\text{if} \quad d > d' \quad \rightarrow \quad \zeta > \zeta'$$

The decrease in the zeta potential results in a decrease in the repulsive forces among the colloidal particles.

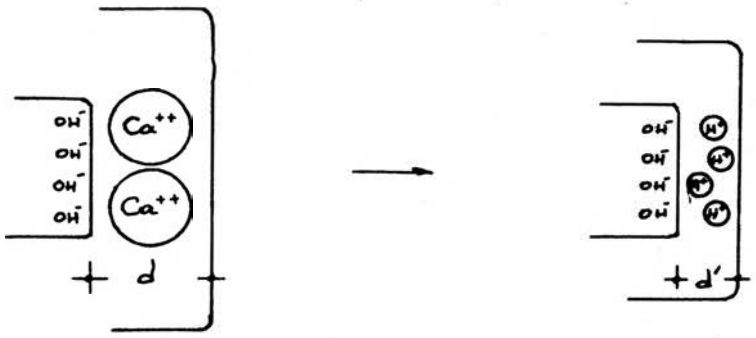



Figure 19. Effect of Exchange of $H^{+}$ Ions for $Ca^{++}$ Ions on "d" Distance.

Explanation of the reasons behind the loss of cohesion upon leaching may be attempted on a physico-chemical basis. The effect of leaching is to replace and remove some of the calcium ions in the soil water system and probably some of the non-hydrated cements. The effect of the removal would be to decrease the amount of pozzolanic reaction

and cement hydration available for a growth in cohesion. Other more complex reactions of a different physico chemical nature may be occurring at the same time, however, the above explanation would appear to be the one of the most significance. The explanation of the gain in friction angle with leaching may be theorized along the same lines since the effect of leaching is, at least in part, an ion exchange function. Since plain tap water was used to represent ground water comparable to that which would be available in nature for leaching, there were exchange ions available such as hydrogen, iron, magnesium, potassium, etc. The exchange of hydrogen or an ion of higher value other than calcium would decrease the zeta potential tc a greater degree.

It can never be claimed that all of the calcium ions of the diffuse layer could be replaced by the hydrogen ions during the leaching process. For the replacement of all of the $Ca^{++}$ with $H^{+}$, it would be necessary to increase the acidity of the water. But on this point it should be remembered that during the leaching great care was taken to assure very accurate duplication of natural leaching conditions. However, organic materials, microbes and the amount of the $Ca^{++}$ which exist in the water and their effect on the chemical or physical changes of the compressive strength has not been considered.

# CONCLUSIONS

The results of this investigation can be summarized in two mutually related groups via:

a) Conditions before leaching which is regular stabilization of the soil, and

b) Condition after leaching.

a - Conditions before leaching

1. As seen in this experiment and in work presented in thesis studies by Leong, Frankenberg, etc., the friability of the soil increases as the lime percentage is increased during the mixing. It is concluded that the friability of the soil varies directly with the amount of lime added to the soil mixture and that lime is more effective than cement.

2. Soil shows an increase in the required optimum moisture content as the admixture percentage of lime is increased before the compaction of the soil. The addition of cement does not affect the moisture content and dry density relations of the soil as greatly as does the hydrated lime, thus indicating it to be less effective in flocculating the soil than the lime.

3. During the mixing the $Ca^{++}$ ions of the hydrated lime move into the diffuse layer. This decreases the zeta potential of the soil particles and as the result of this, in general, an increase in the strength characteristics of the soil can be seen. The test results from the triaxial compression test show that the increase in the strength of the soil is directly proportional to the amount of the admixture.

4. A greater increase in the angle of friction is seen through the use of lime than through the use of cement. Also an increase in

the cohesion is seen by the addition of the lime and cement admixtures. But the cement results in a greater increase in cohesion than does the use of lime.

b - Conditions after leaching

1. As seen above in our discussion and the resulting data obtained, a gain in the strength of the stabilized soil is observed after leaching, due to the physical and chemical changes,

2. During the leaching the removal of the $Ca^{++}$ particles takes place under the effect of the water.

3. The gain in the angle of friction of the stabilized soil may be the result of the ion exchange between the calcium particles of the hydrated lime and cement, and the $H^{+}$ ions of the water. If any excessive exchange occurred between $Ca^{++}$ and aluminum and iron of the tap water, this also effected the strengthening of the soil. The increase in the angle of friction upon leaching appears to diminish as the cement content increases for each lime content. The reason for gain in the friction angle may be theorized along the same lines.

4. The leaching of the specimen results in a loss of cohesion and the loss increases, relative to the cohesion of the unleached samples, as the percent cement is increased for each percent of lime. The loss of cohesion upon leaching is due to the decrease of the pozzolanic reaction, cement hydration and the other more complex physio-chemical reactions.

5. During the leaching some of the calcium particles can be seen at the surface of the specimens and there is a little disintegration of the specimen which changes with the amount of the additive mixture.

In this investigation the effect of flocculation took place which was observable by the normal eye sight. But for the realization of the more complex chemical reaction like pozzolanic reaction and carbonation, etc., which can only be observed by precise scientific instruments, the author believes that in the future by using an X-ray diffraction machine or other scientific methods, the effect of the pozzolanic reaction, flocculation, and carbonation will be determined and will be helpful for soil engineers.

# APPENDIX A

# DRY DENSITY AND MOISTURE CONTENT OF STABILIZED AND LEACHED SOIL

| Mixture Lime | Cem. | # | Wet Wt. grms. | Dry Wt. grms. | Dry Density lb/cu.ft. | Moist. Cont. % |
|---|---|---|---|---|---|---|
| | Optimum moisture of natural soil | | | | – | 20.25 |
| 2 | 0 | 1 | 127.80 | 104.70 | 97.– | 22.10 |
| | | 2 | 127.40 | 104.45 | 96.90 | 22.– |
| | | 3 | 127.70 | 104.50 | 96.85 | 22.20 |
| | | 4 | 127.20 | 104.10 | 96.30 | 22.15 |
| | 2 | 1 | 127.30 | 104.10 | 96.25 | 22.25 |
| | | 2 | 127.10 | 103.95 | 96.– | 22.30 |
| | | 3 | 127.40 | 104.20 | 96.35 | 22.20 |
| | | 4 | 127.05 | 104.– | 96.10 | 22.15 |
| | 4 | 1 | 127.10 | 103.90 | 95.90 | 22.35 |
| | | 2 | 126.95 | 103.80 | 95.85 | 22.30 |
| | | 3 | 126.70 | 103.65 | 95.70 | 22.25 |
| | | 4 | 126.85 | 103.70 | 95.60 | 22.35 |
| | 6 | 1 | 126.90 | 103.75 | 95.65 | 22.35 |
| | | 2 | 126.70 | 103.60 | 95.60 | 22.30 |
| | | 3 | 126.50 | 103.45 | 95.50 | 22.30 |
| | | 4 | 126.85 | 103.20 | 95.– | 22.90 |
| 4 | 0 | 1 | 126.60 | 103.– | 94.90 | 22.90 |
| | | 2 | 126.20 | 102.70 | 94.45 | 22.90 |
| | | 3 | 126.45 | 102.85 | 94.45 | 22.95 |
| | | 4 | 126.30 | 102.75 | 94.45 | 22.90 |
| | 2 | 1 | 126.– | 102.55 | 94.30 | 22.80 |
| | | 2 | 126.10 | 102.50 | 94.20 | 23.– |
| | | 3 | 125.80 | 102.30 | 94.10 | 22.95 |
| | | 4 | 125.80 | 102.20 | 94.– | 23.10 |

Table. 1. Dry Density and Moisture Content of Stabilized Soil

| Mixture Lime | Mixture Cem. | Mixture # | Wet Wt. grms. | Dry Wt. grms. | Dry Density lb/cu.ft | Moist Cont % |
|---|---|---|---|---|---|---|
| 4 | 4 | 1 | 125.80 | 102.40 | 94.30 | 22.85 |
| | | 2 | 125.80 | 102.20 | 93.85 | 23.05 |
| | | 3 | 125.70 | 102.05 | 93.55 | 23.15 |
| | | 4 | 125.40 | 102.– | 93.80 | 22.95 |
| | 6 | 1 | 125.50 | 102.– | 93.60 | 23.05 |
| | | 2 | 125.30 | 101.95 | 93.75 | 22.95 |
| | | 3 | 125.30 | 101.85 | 93.50 | 23.– |
| | | 4 | 125.40 | 102.– | 93.85 | 22.95 |
| 6 | 0 | 1 | 126.20 | 102.20 | 93.50 | 23.50 |
| | | 2 | 125.95 | 102.– | 93.45 | 23.50 |
| | | 3 | 125.70 | 101.90 | 93.40 | 23.40 |
| | | 4 | 125.50 | 101.50 | 92.75 | 23.65 |
| | 2 | 1 | 125.45 | 101.60 | 93.– | 23.50 |
| | | 2 | 125.40 | 101.50 | 92.95 | 23.55 |
| | | 3 | 125.40 | 101.60 | 93.– | 23.40 |
| | | 4 | 125.10 | 101.30 | 92.70 | 23.50 |
| | 4 | 1 | 125.15 | 101.40 | 92.90 | 23.40 |
| | | 2 | 125.20 | 101.25 | 92.60 | 23.65 |
| | | 3 | 125.– | 101.– | 92.25 | 23.80 |
| | | 4 | 124.90 | 100.95 | 92.15 | 23.75 |
| | 6 | 1 | 125.– | 100.95 | 92.– | 23.90 |
| | | 2 | 124.85 | 100.70 | 91.80 | 24.– |
| | | 3 | 124.55 | 100.50 | 91.70 | 23.90 |
| | | 4 | 124.70 | 100.55 | 91.50 | 24.05 |

Table.1. Dry Density and Moisture Content of Stabilized Soil

| Mixture Lime | Mixture Cem. | Mixture # | Wet Wt. grms. | Dry Wt. grms. | Dry Density lb/cu.ft | Moist. Cont % |
|---|---|---|---|---|---|---|
| 2 | 0 | 1 | 127.60 | | | |
| | | 2 | 187.40 | | | |
| | | 3 | 127.30 | | | |
| | | 4 | 127.50 | | | |
| | 2 | 1 | 127.40 | 104.25 | 96.35 | 22.20 |
| | | 2 | 127.20 | 104.— | 96.— | 22.30 |
| | | 3 | 127.30 | 103.90 | 95.90 | 22.50 |
| | | 4 | 127.— | 103.85 | 95.80 | 22.30 |
| | 4 | 1 | 127.— | 103.90 | 95.90 | 22.25 |
| | | 2 | 126.80 | 103.20 | 95.25 | 22.85 |
| | | 3 | 126.90 | 103.70 | 95.50 | 22.40 |
| | | 4 | 126.70 | 103.40 | 95.40 | 22.55 |
| | 6 | 1 | 126.50 | 103.25 | 95.15 | 22.50 |
| | | 2 | 126.70 | 103.50 | 95.50 | 22.40 |
| | | 3 | 126.85 | 103.70 | 95.60 | 22.35 |
| | | 4 | 126.80 | 103.60 | 95.50 | 22.40 |
| 4 | 0 | 1 | 126.50 | 103.20 | 95.15 | 22.55 |
| | | 2 | 126.40 | 103.— | 95.— | 22.70 |
| | | 3 | 126.20 | 102.75 | 94.50 | 22.80 |
| | | 4 | 126.35 | 102.90 | 94.80 | 22.80 |
| | 2 | 1 | 126.20 | 102.50 | 94.10 | 23.10 |
| | | 2 | 126.80 | 102.35 | 94.15 | 22.90 |
| | | 3 | 126.— | 102.65 | 94.40 | 22.75 |
| | | 4 | 125.80 | 102.40 | 94.20 | 22.85 |

Table. 1. Dry Density and Moisture Content of Leached Soil

| Mixture Lime | Mixture Cem. | # | Wet Wt. grms. | Dry Wt. grms. | Dry Density lb/cu.ft. | Moist. Cont % |
|---|---|---|---|---|---|---|
| 4 | 4 | 1 | 125.70 | 103.35 | 94.20 | 22.80 |
| | | 2 | 125.50 | 102.10 | 93.85 | 22.90 |
| | | 3 | 125.65 | 102.15 | 93.90 | 22.95 |
| | | 4 | 125.70 | 102.— | 93.50 | 23.20 |
| | 6 | 1 | 125.30 | 101.95 | 93.70 | 22.95 |
| | | 2 | 125.20 | 101.80 | 93.45 | 23.15 |
| | | 3 | 125.20 | 101.75 | 93.45 | 23.05 |
| | | 4 | 125.40 | 102.05 | 93.70 | 22.85 |
| 6 | 0 | 1 | 126.— | 102.10 | 93.45 | 23.40 |
| | | 2 | 125.90 | 101.85 | 93.15 | 23.60 |
| | | 3 | 125.85 | 101.95 | 93.20 | 23.45 |
| | | 4 | 125.60 | 101.70 | 93.10 | 23.50 |
| | 2 | 1 | 125.50 | 101.70 | 93.15 | 23.40 |
| | | 2 | 125.30 | 101.50 | 93.— | 23.45 |
| | | 3 | 125.25 | 101.50 | 93.05 | 23.40 |
| | | 4 | 125.25 | 101.40 | 92.90 | 23.50 |
| | 4 | 1 | 125.20 | 101.30 | 92.70 | 23.55 |
| | | 2 | 125.— | 101.90 | 92.— | 23.90 |
| | | 3 | 125.15 | 101.95 | 91.90 | 24.— |
| | | 4 | 124.95 | 101.10 | 92.40 | 23.60 |
| | 6 | 1 | 124.95 | 100.70 | 91.70 | 24.05 |
| | | 2 | 124.80 | 100.50 | 91.35 | 24.15 |
| | | 3 | 124.60 | 100.90 | 92.30 | 23.50 |
| | | 4 | 124.70 | 100.60 | 91.55 | 24.— |

Table.1. Dry Density and Moisture Content of Leached Soil

# APPENDIX B

## RESULTS OF TRIAXIAL COMPRESSION TESTS ON STABILIZED AND LEACHED SOIL

## LIME 2 %

| Additive % By Wt. | Failure Stress | | | | |
|---|---|---|---|---|---|
| | Lateral Pressure | | Strain at Failure | | Axial Stress P.S.I. |
| | Before Leach. | After Leach | Test | Average | |
| 0 % Cement | 0 | | 80 | 70 | 63 |
| | 0 | | 60 | | |
| | 60 | | 150 | 160 | 206 |
| | 60 | | 170 | | |
| | | 0 | Broken | | Broken |
| | | 0 | Broken | | |
| | | 60 | Broken | | Broken |
| | | 60 | Broken | | |
| 2 % Cement | 0 | | 80 | 85 | 78 |
| | 0 | | 90 | | |
| | 60 | | 200 | 190 | 232 |
| | 60 | | 180 | | |
| | | 0 | 90 | 90 | 32 |
| | | 0 | 85 | | |
| | | 60 | 240 | 225 | 265 |
| | | 60 | 210 | | |
| 4 % Cement | 0 | | 120 | 115 | 104 |
| | 0 | | 110 | | |
| | 60 | | 230 | 240 | 278 |
| | 60 | | 250 | | |
| | | 0 | 120 | 115 | 104 |
| | | 0 | 110 | | |
| | | 60 | 270 | 255 | 292 |
| | | 60 | 240 | | |
| 6 % Cement | 0 | | 140 | 130 | 118 |
| | 0 | | 120 | | |
| | 60 | | 240 | 260 | 297 |
| | 60 | | 280 | | |
| | | 0 | 130 | 125 | 114 |
| | | 0 | 120 | | |
| | | 60 | 280 | 285 | 319 |
| | | 60 | 290 | | |

Table 2. Results of Triaxial Compression Tests on Stabilized and Leached Soil

LIME 4%

| ADDITIVE % BY WT. | FAILURE STRESS | | | | |
|---|---|---|---|---|---|
| | LATERAL PRESSURE | | STRAIN AT FAILURE. | | AXIAL STRESS PSI. |
| | BEFORE LEACH. | AFTER LEACH. | TEST | AVARAGE | |
| 0 % CEMENT | 0 | | 80 | 85 | 78 |
| | 0 | | 90 | | |
| | 60 | | 240 | 230 | 269 |
| | 60 | | 220 | | |
| | | 0 | 100 | 95 | 87 |
| | | 0 | 90 | | |
| | | 60 | 260 | 265 | 301 |
| | | 60 | 270 | | |
| 2 % CEMENT | 0 | | 110 | 115 | 104 |
| | 0 | | 120 | | |
| | 60 | | 290 | 270 | 306 |
| | 60 | | 250 | | |
| | | 0 | 120 | 115 | 104 |
| | | 0 | 110 | | |
| | | 60 | 310 | 300 | 332 |
| | | 60 | 290 | | |
| 4 % CEMENT | 0 | | 130 | 140 | 128 |
| | 0 | | 150 | | |
| | 60 | | 300 | 320 | 351 |
| | 60 | | 340 | | |
| | | 0 | 150 | 145 | 133 |
| | | 0 | 140 | | |
| | | 60 | 350 | 360 | 387 |
| | | 60 | 370 | | |
| 6 % CEMENT | 0 | | 160 | 150 | 137 |
| | 0 | | 140 | | |
| | 60 | | 330 | 345 | 374 |
| | 60 | | 360 | | |
| | | 0 | 140 | 150 | 137 |
| | | 0 | 160 | | |
| | | 60 | 380 | 370 | 396 |
| | | 60 | 360 | | |

Table 2. RESULTS OF TRIAXIAL COMPRESSION TESTS ON STABILIZED AND LEACHED SOIL

LIME 6 %

| Additive % By Wt. | Failure Stress | | | | |
|---|---|---|---|---|---|
| | Lateral Pressure | | Strain at Failure | | Axial Stress psi. |
| | Before Leach. | After Leach. | Test | Avarage | |
| 0 % Cement | 0 | | 140 | 135 | 123 |
| | 0 | | 130 | | |
| | 60 | | 300 | 320 | 351 |
| | 60 | | 340 | | |
| | | 0 | 120 | 130 | 118 |
| | | 0 | 140 | | |
| | | 60 | 350 | 365 | 391 |
| | | 60 | 380 | | |
| 2 % Cement | 0 | | 140 | 155 | 141 |
| | 0 | | 170 | | |
| | 60 | | 380 | 370 | 396 |
| | 60 | | 360 | | |
| | | 0 | 180 | 175 | 159 |
| | | 0 | 170 | | |
| | | 60 | 400 | 410 | 432 |
| | | 60 | 420 | | |
| 4 % Cement | 0 | | 200 | 180 | 163 |
| | 0 | | 170 | | |
| | 60 | | 390 | 400 | 424 |
| | 60 | | 410 | | |
| | | 0 | 180 | 180 | 163 |
| | | 0 | 180 | | |
| | | 60 | 450 | 435 | 460 |
| | | 60 | 420 | | |
| 6 % Cement | 0 | | 180 | 190 | 173 |
| | 0 | | 200 | | |
| | 60 | | 420 | 415 | 438 |
| | 60 | | 410 | | |
| | | 0 | 200 | 185 | 169 |
| | | 0 | 170 | | |
| | | 60 | 430 | 440 | 470 |
| | | 60 | 450 | | |

Table 2. Results of Triaxial Compression Tests on Stabilized and Leached Soil

# APPENDIX C

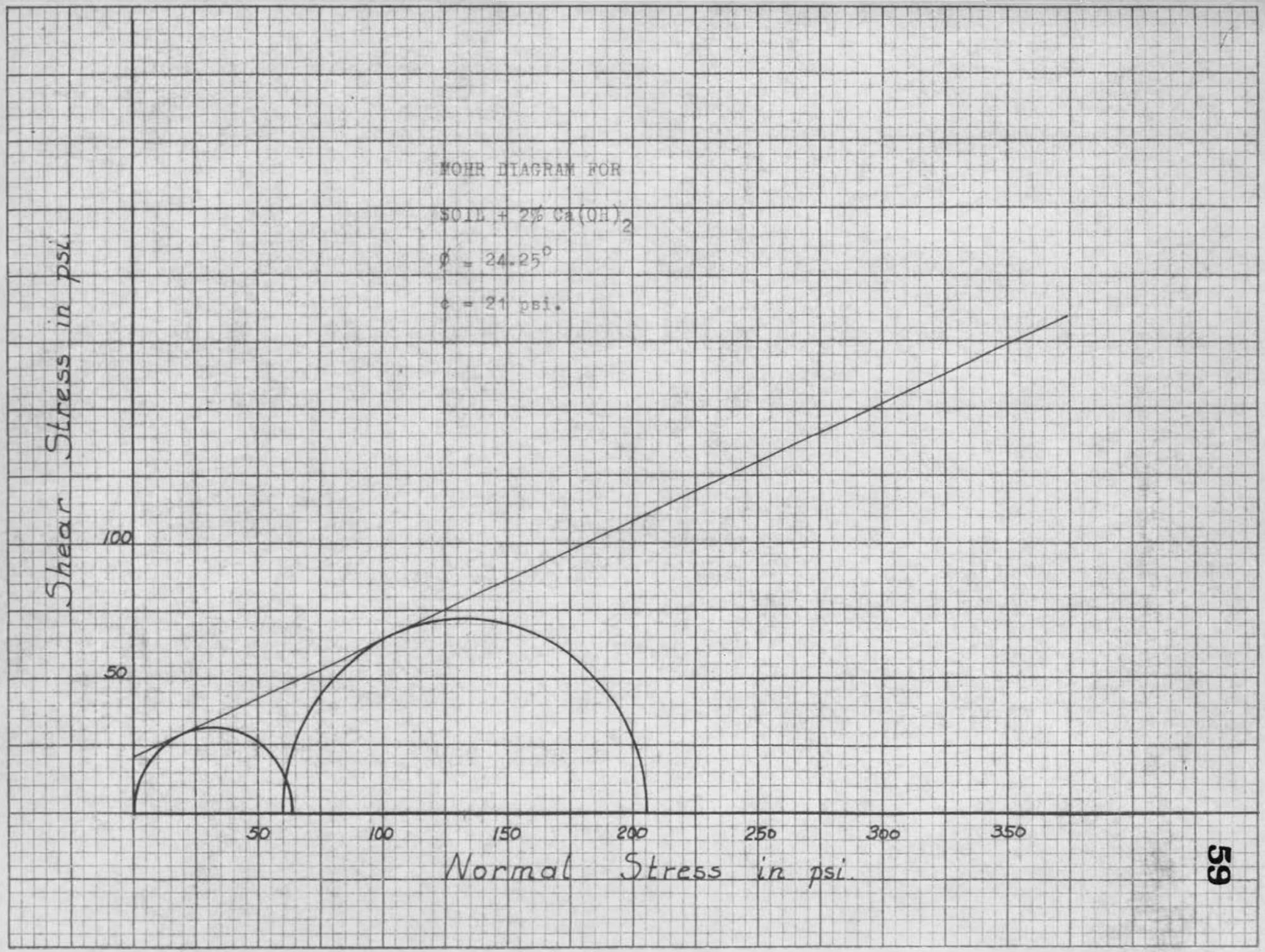
## CHANGE IN THE FRICTION ANGLE AND THE COHESION BEFORE AND AFTER LEACHING

| Lime % | Cement % | tg ϕ | ϕ | c | tg ϕ′ | ϕ′ | c′ |
|---|---|---|---|---|---|---|---|
| | | Before Leaching | | | After Leaching | | |
| 2 | 0 | 0.45 | 24.25° | 21 | | | |
| | 2 | 0.49 | 26.1° | 25 | 0.575 | 29.9° | 24 |
| | 4 | 0.54 | 28.5° | 32 | 0.60 | 31° | 30 |
| | 6 | 0.568 | 29.6° | 35 | 0.640 | 32.6° | 32 |
| 4 | 0 | 0.59 | 30.5° | 23 | 0.672 | 33.9° | 23 |
| | 2 | 0.644 | 32.8° | 28 | 0.721 | 35.8° | 26 |
| | 4 | 0.709 | 35.3° | 34 | 0.778 | 37.9° | 32 |
| | 6 | 0.729 | 36.1° | 35 | 0.81 | 39° | 33 |
| 6 | 0 | 0.728 | 35.9° | 30 | 0.82 | 39.4° | 28 |
| | 2 | 0.784 | 38.1° | 35 | 0.85 | 40.4° | 36 |
| | 4 | 0.807 | 38.9° | 39 | 0.875 | 41.3° | 37 |
| | 6 | 0.83 | 39.7° | 41 | 0.89 | 42° | 38 |

Table 3. Change in the Friction Angle and the Cohesion Before and After Leaching.

# APPENDIX D

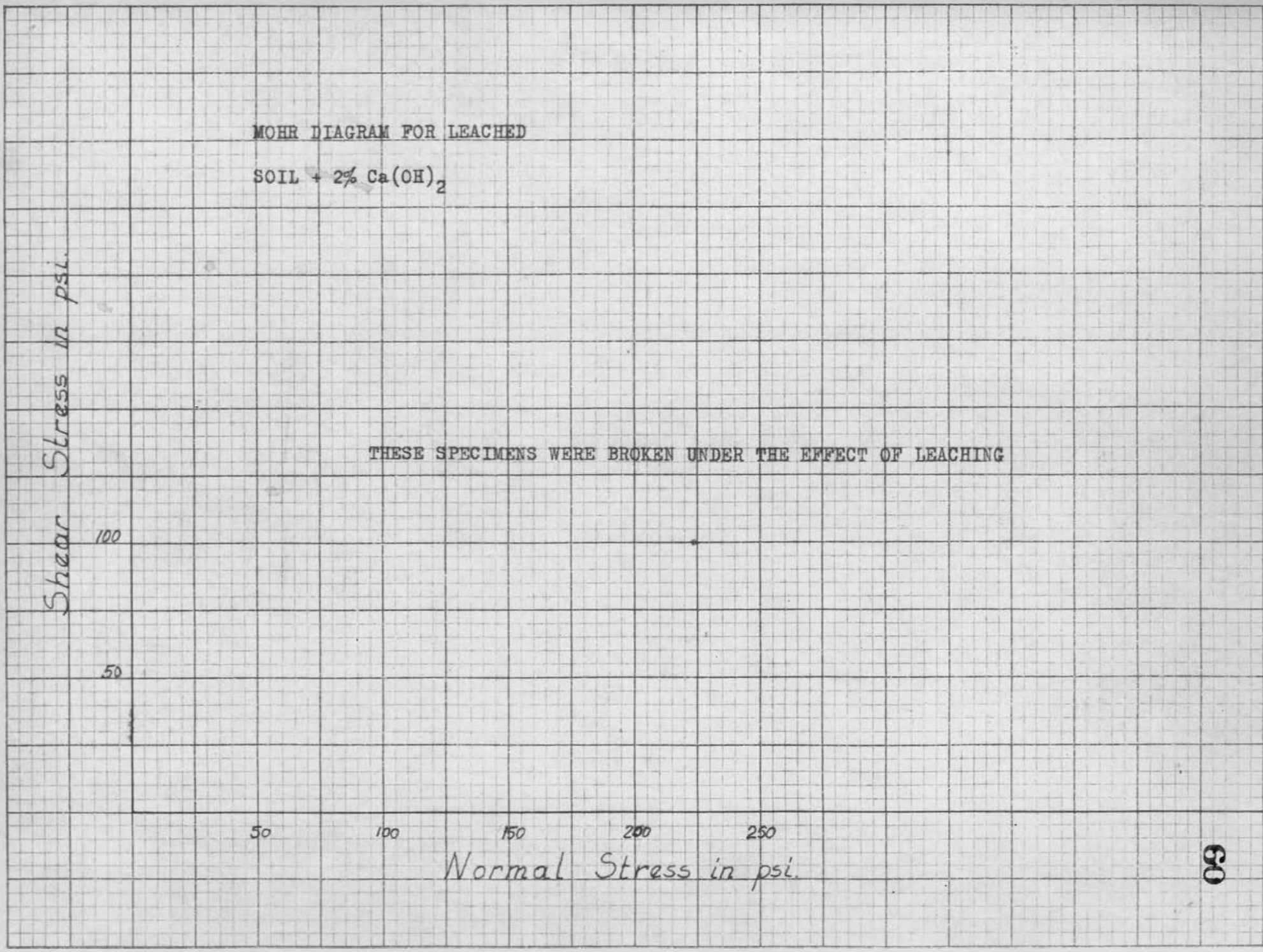
## MOHR DIAGRAMS FOR TRIAXIAL COMPRESSION TEST

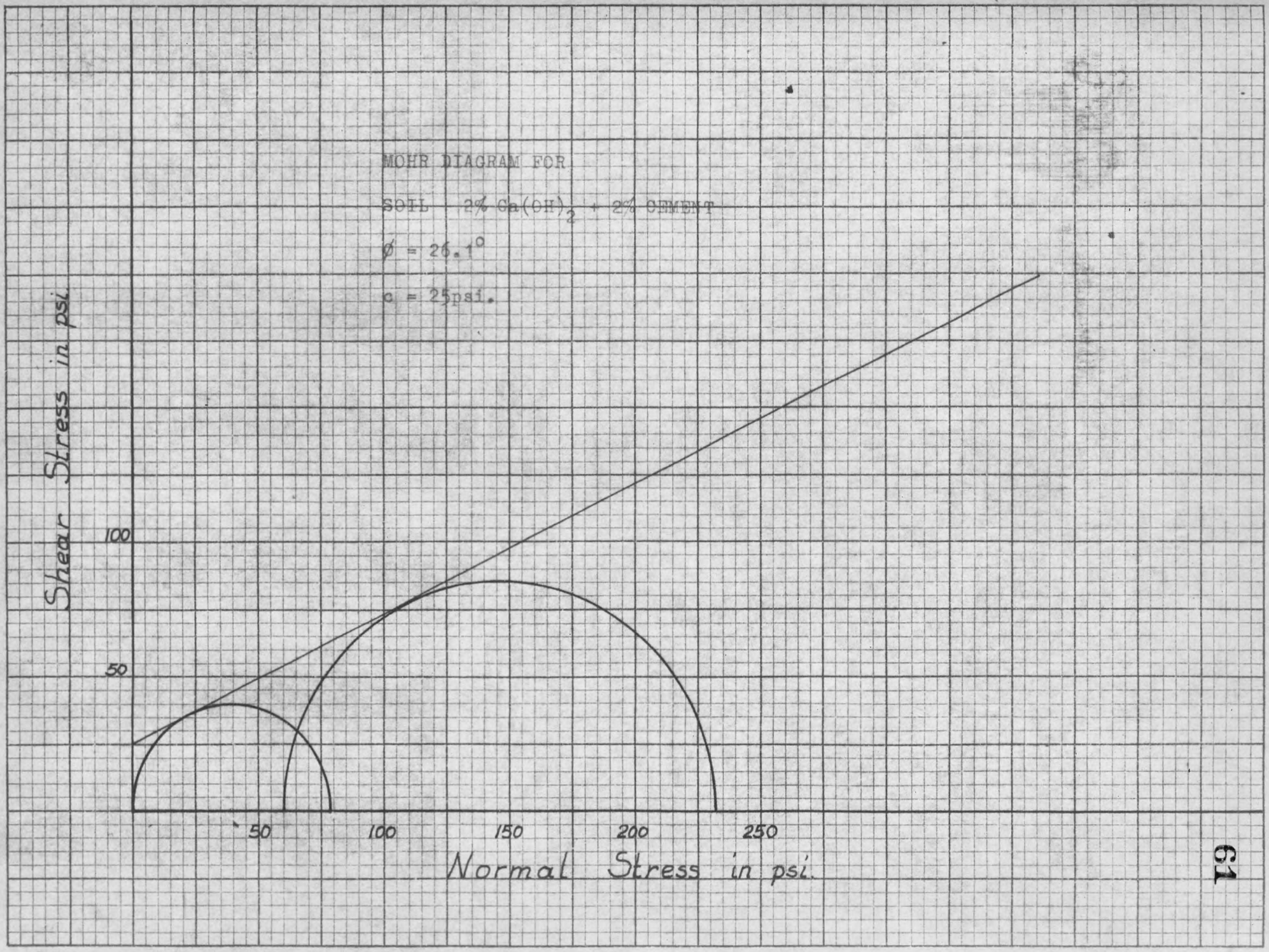

MOHR DIAGRAM FOR
SOIL + 2% Ca(OH)2
ϕ = 24.25°
c = 21 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

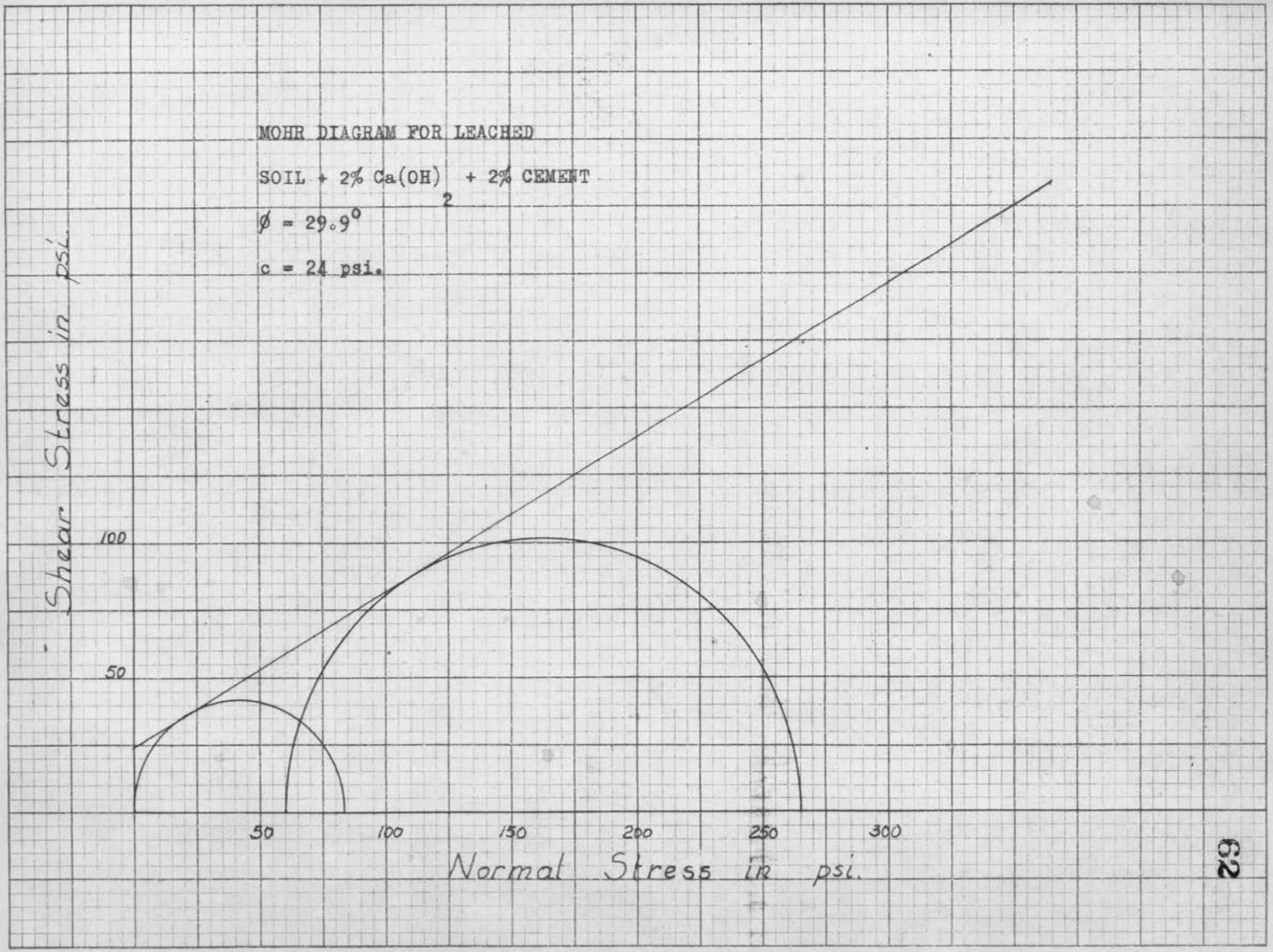
MOHR DIAGRAM FOR LEACHED

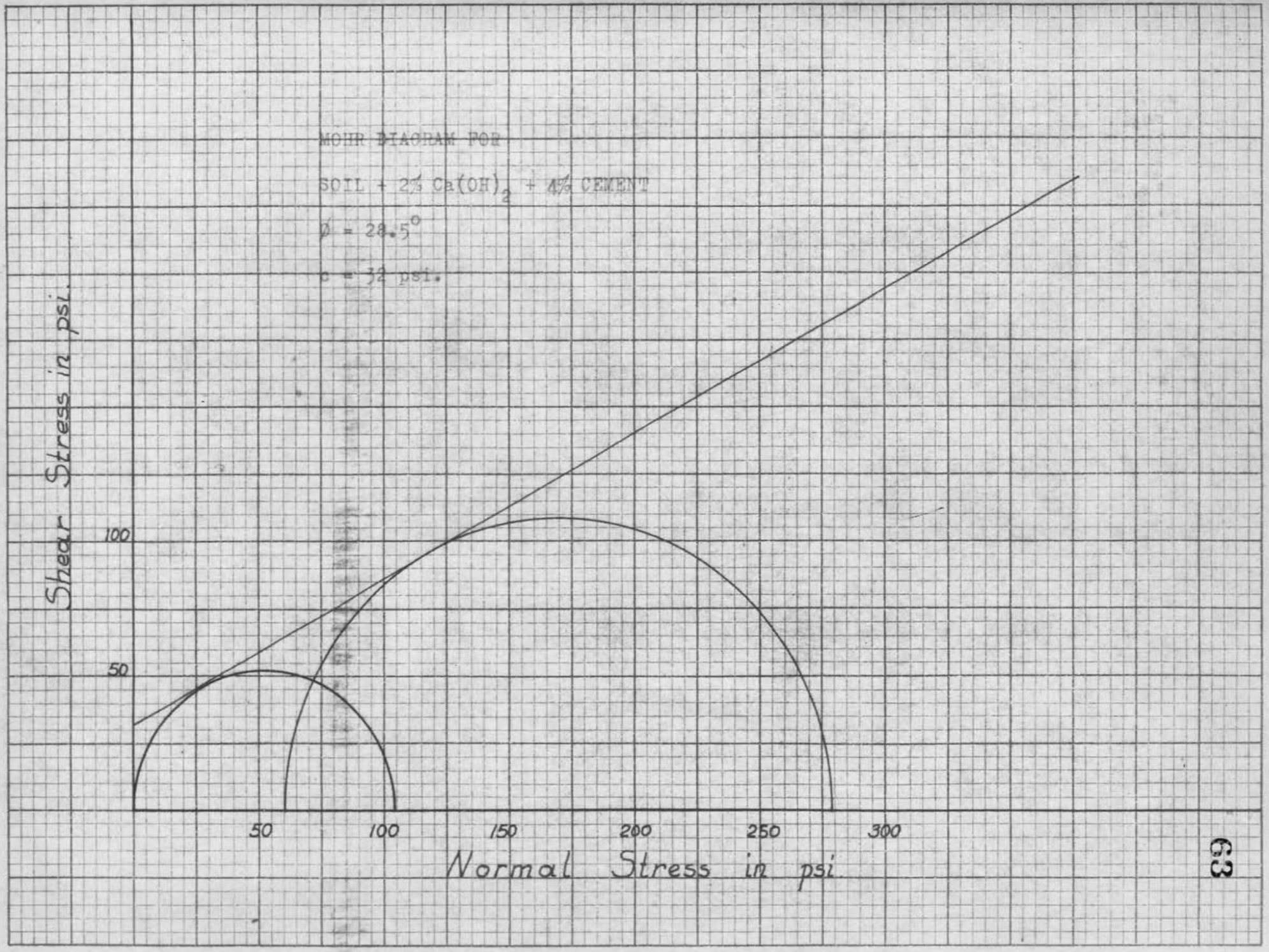
SOIL + 2% $Ca(OH)_2$

THESE SPECIMENS WERE BROKEN UNDER THE EFFECT OF LEACHING




MOHR DIAGRAM FOR
SOIL 2% Ca(OH)2 + 2% CEMENT
ϕ = 26.1°
c = 25psi.
Shear Stress in psi
100
50
50
100
150
200
250
Normal Stress in psi.


MOHR DIAGRAM FOR LEACHED
SOIL + 2% Ca(OH)2 + 2% CEMENT
ϕ = 29.9°
c = 24 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
Normal Stress in psi.

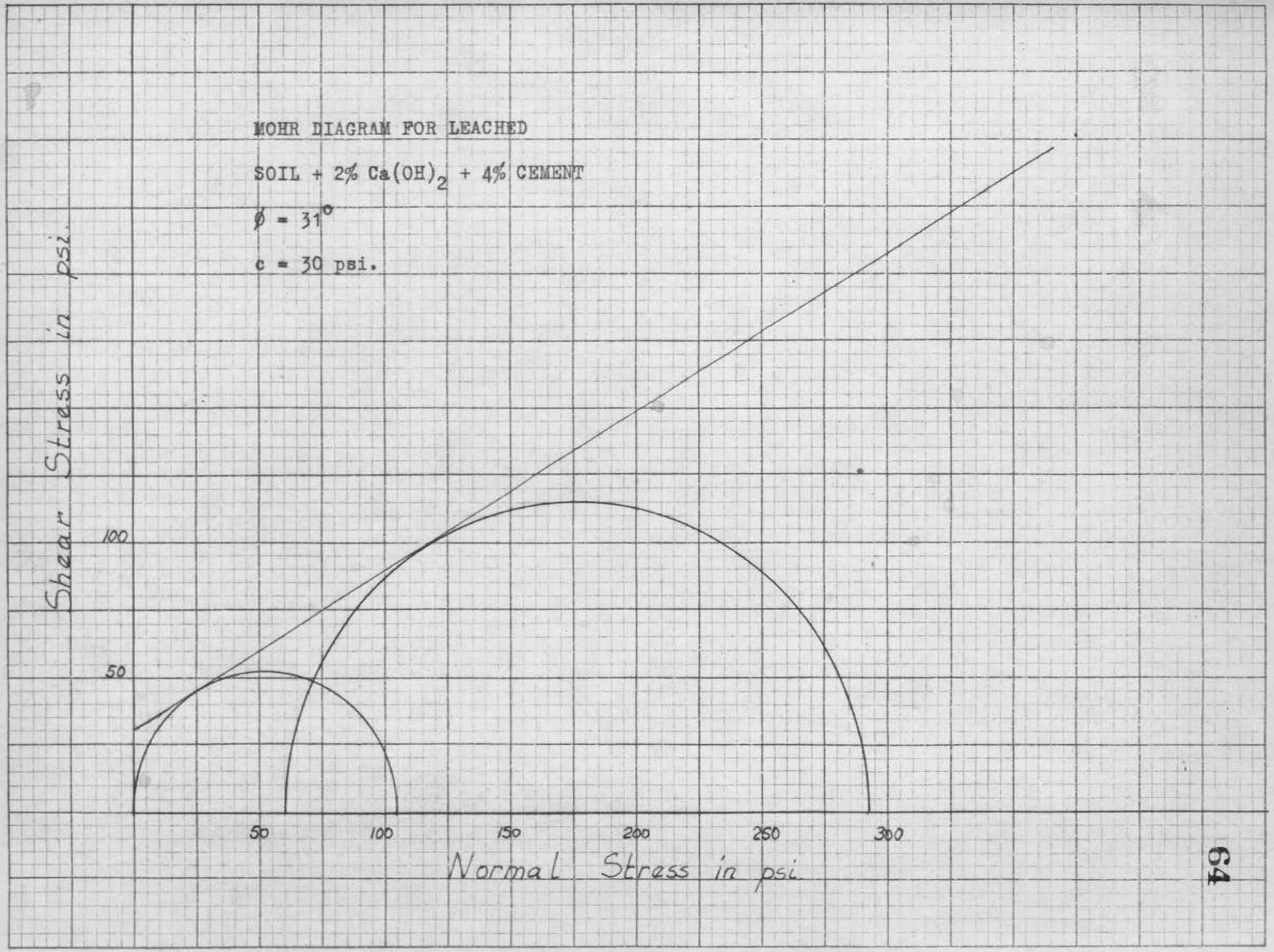

MOHR DIAGRAM FOR
SOIL + 2% Ca(OH)2 + 4% CEMENT
ϕ = 28.5°
c = 32 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
Normal Stress in psi.

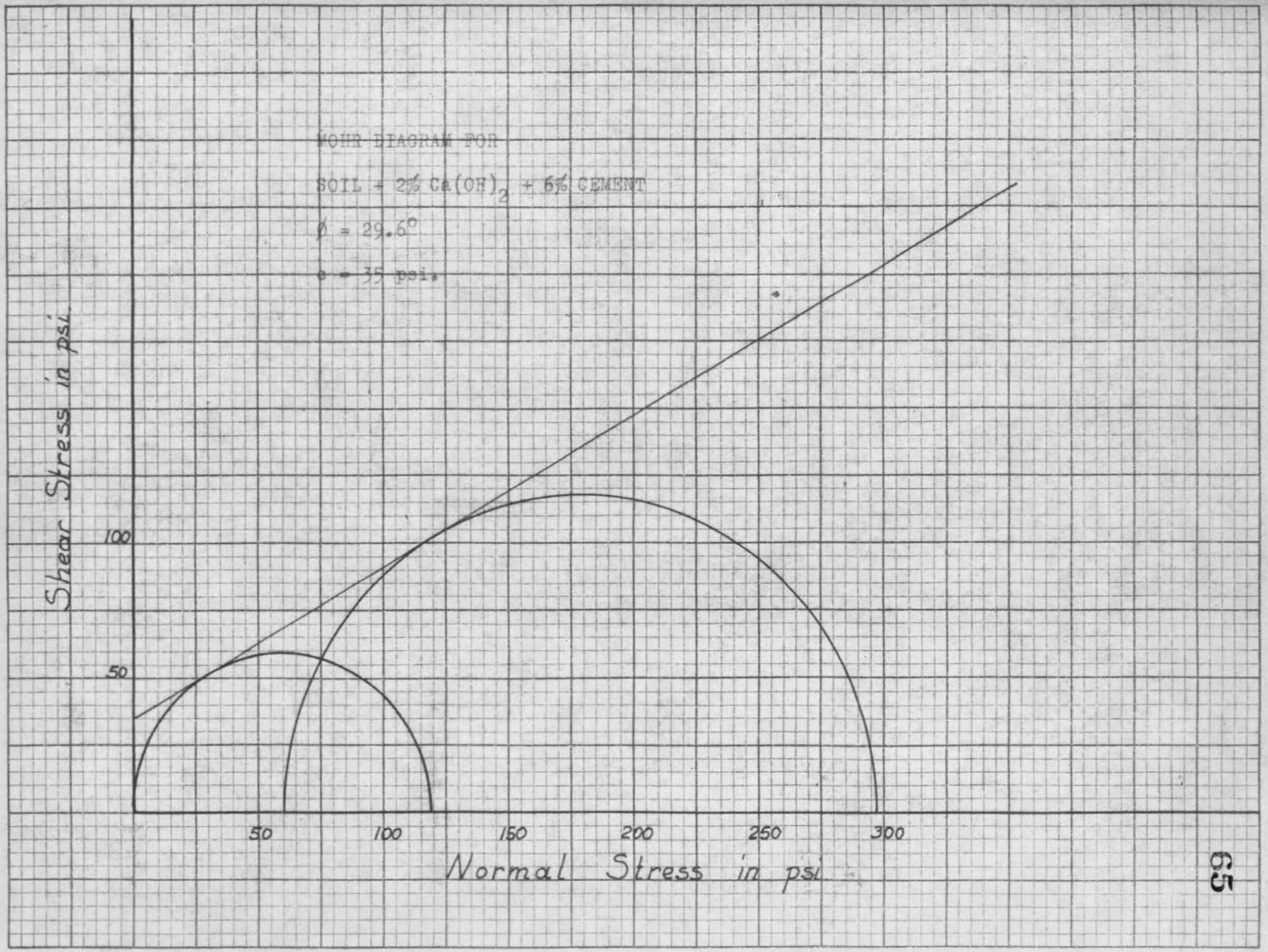
MOHR DIAGRAM FOR LEACHED

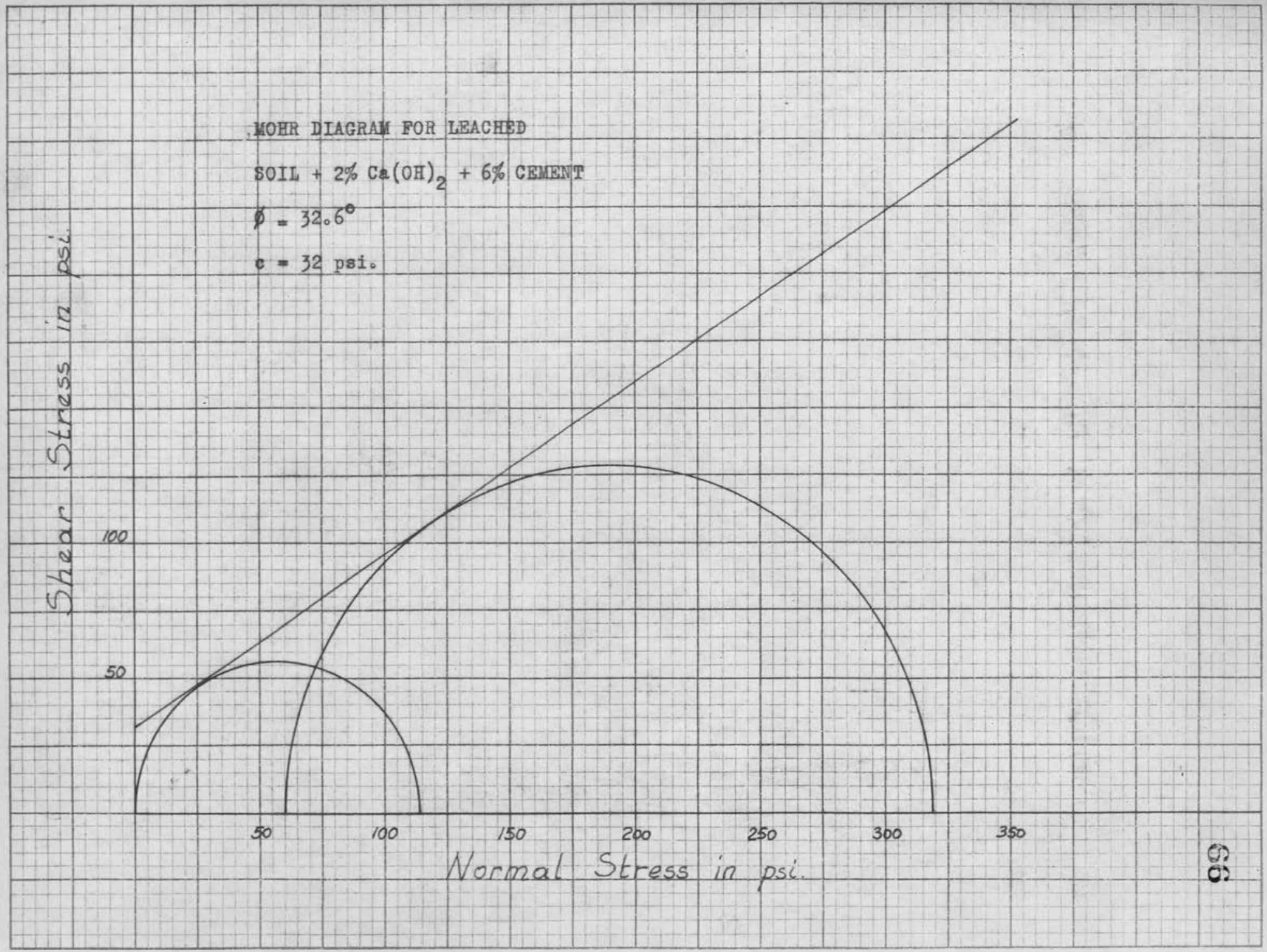
SOIL + 2% $Ca(OH)_2$ + 4% CEMENT

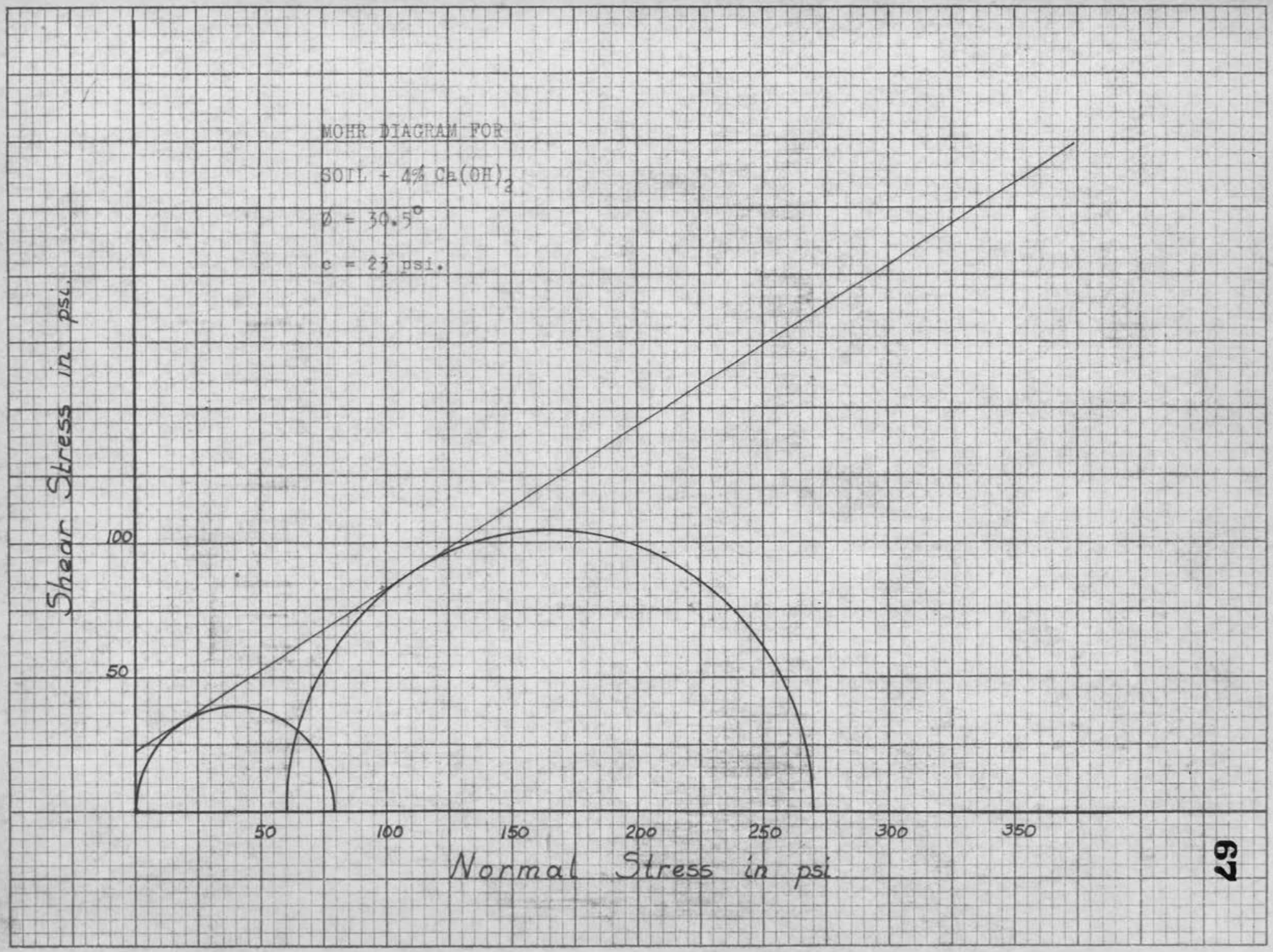
$\phi = 31^{\circ}$

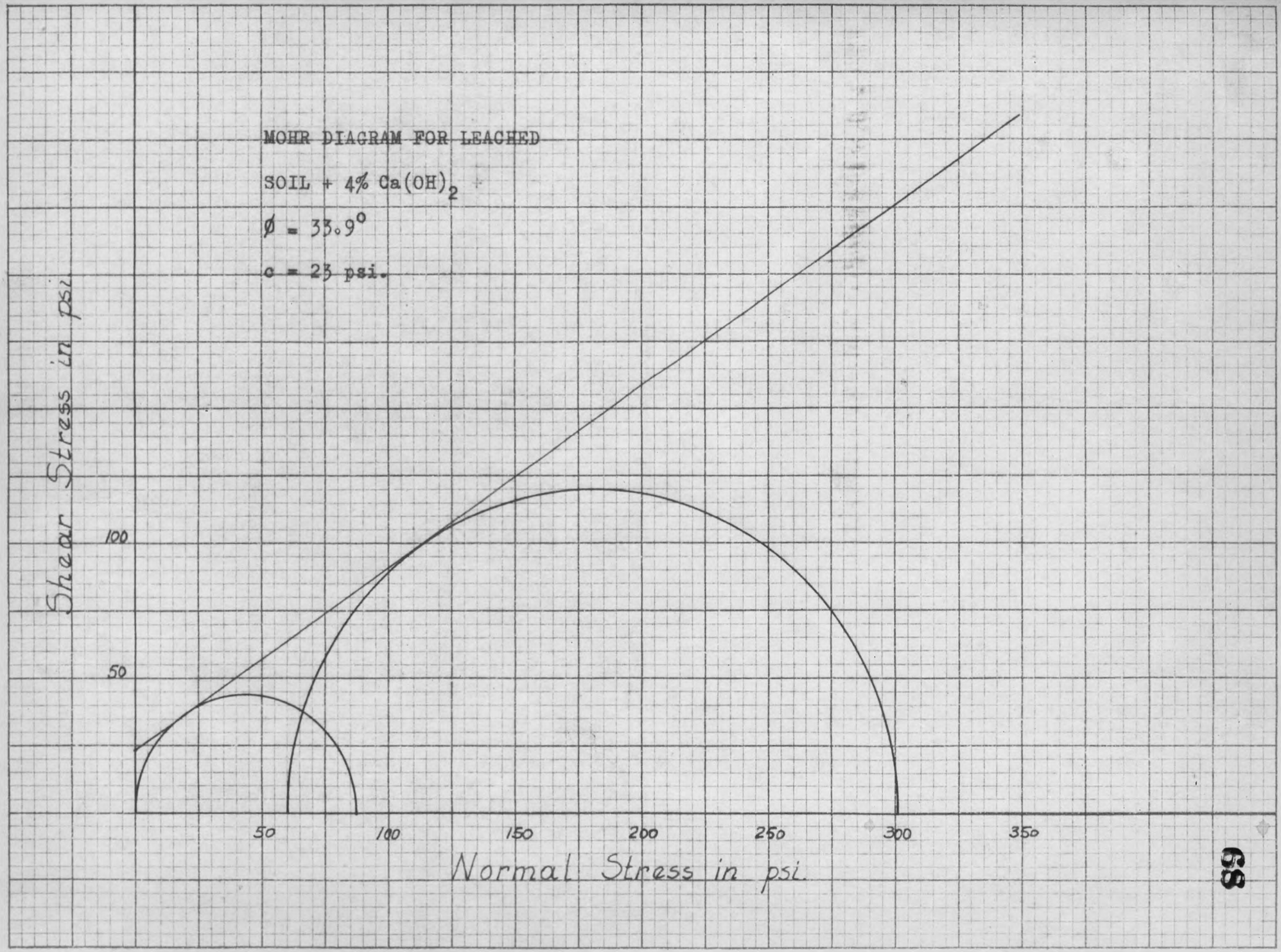
c = 30 psi.

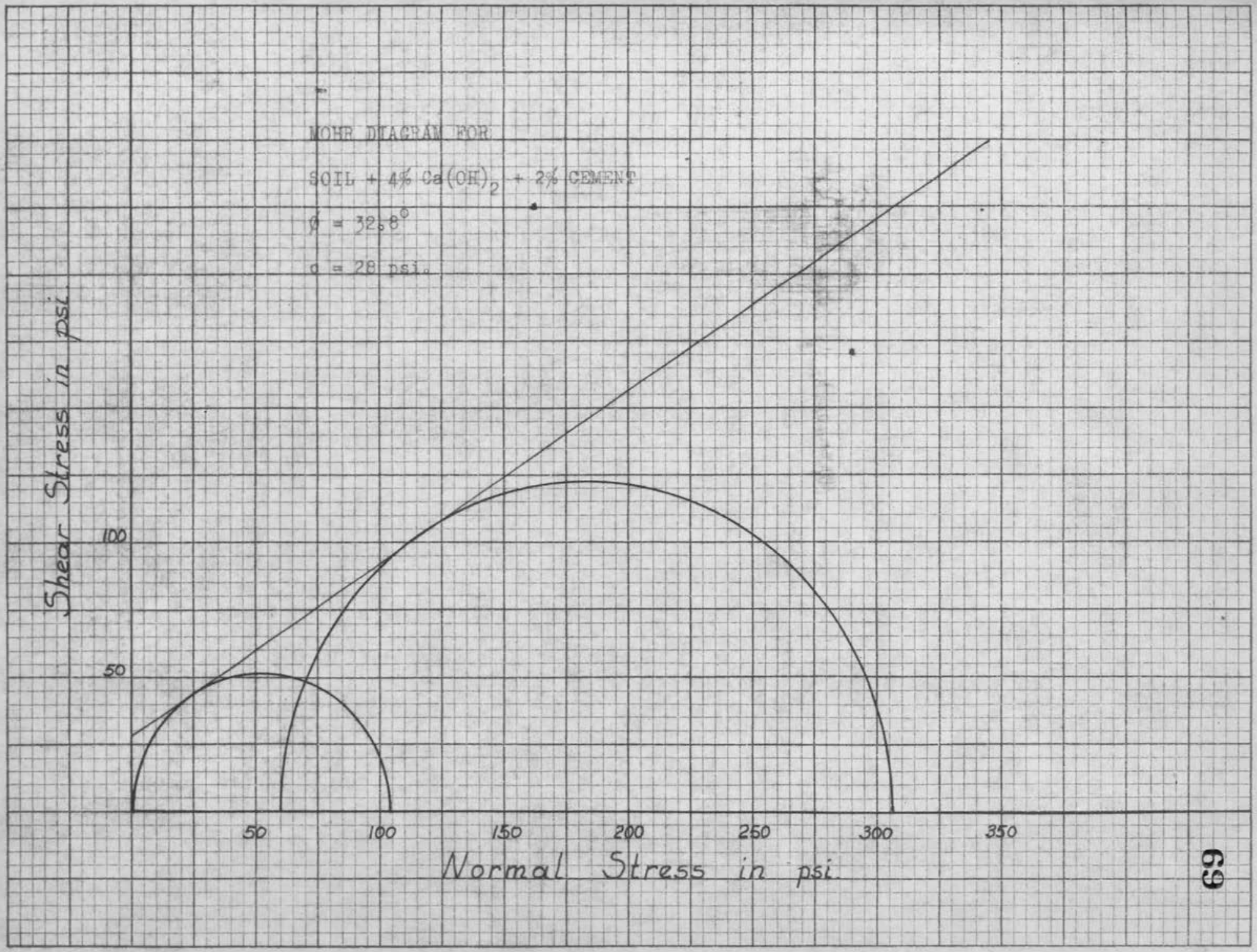


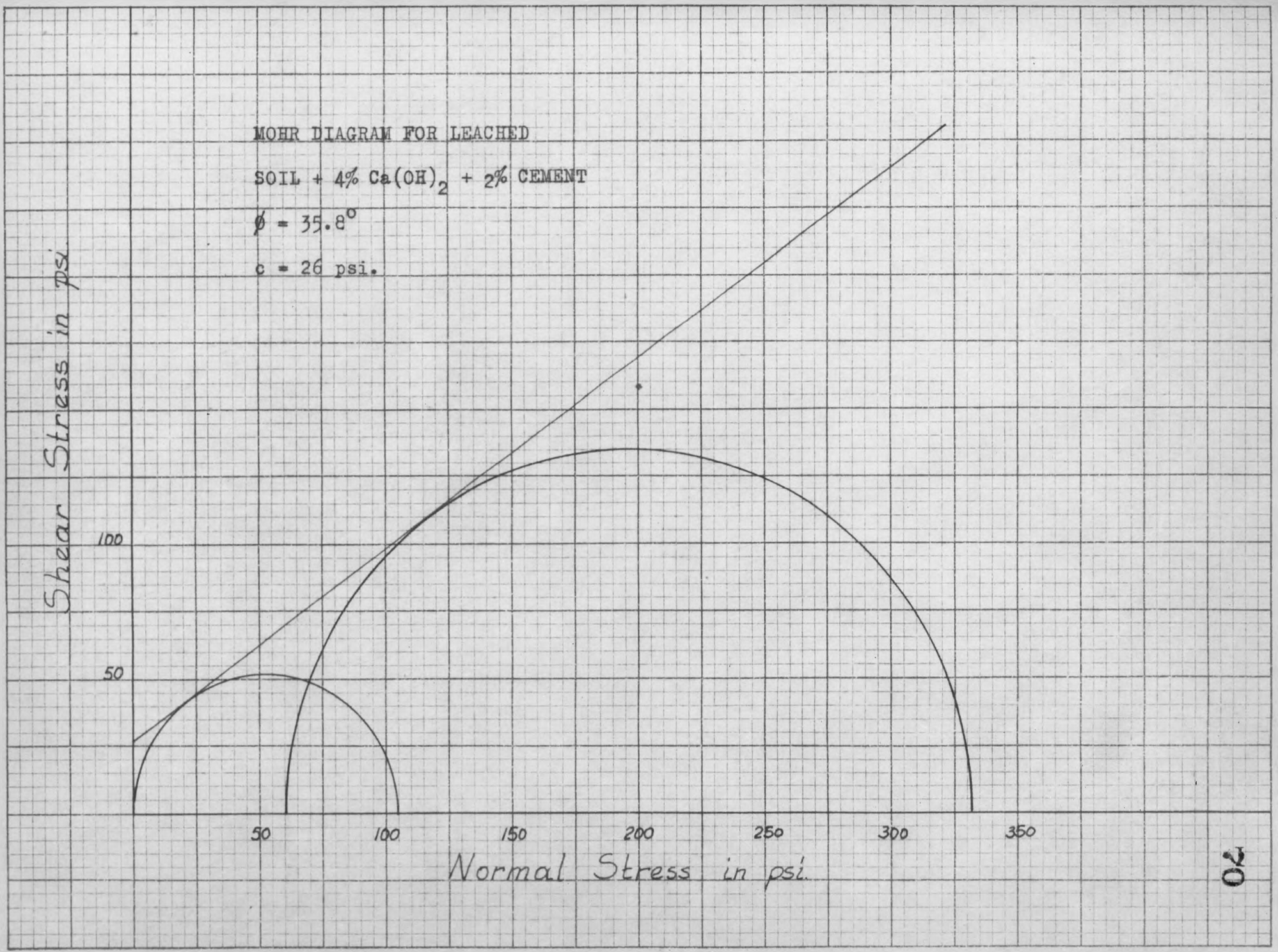

MOHR DIAGRAM FOR
SOIL + 2% Ca(OH)2 + 6% CEMENT
ϕ = 29.6°
c = 35 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
Normal Stress in psi.

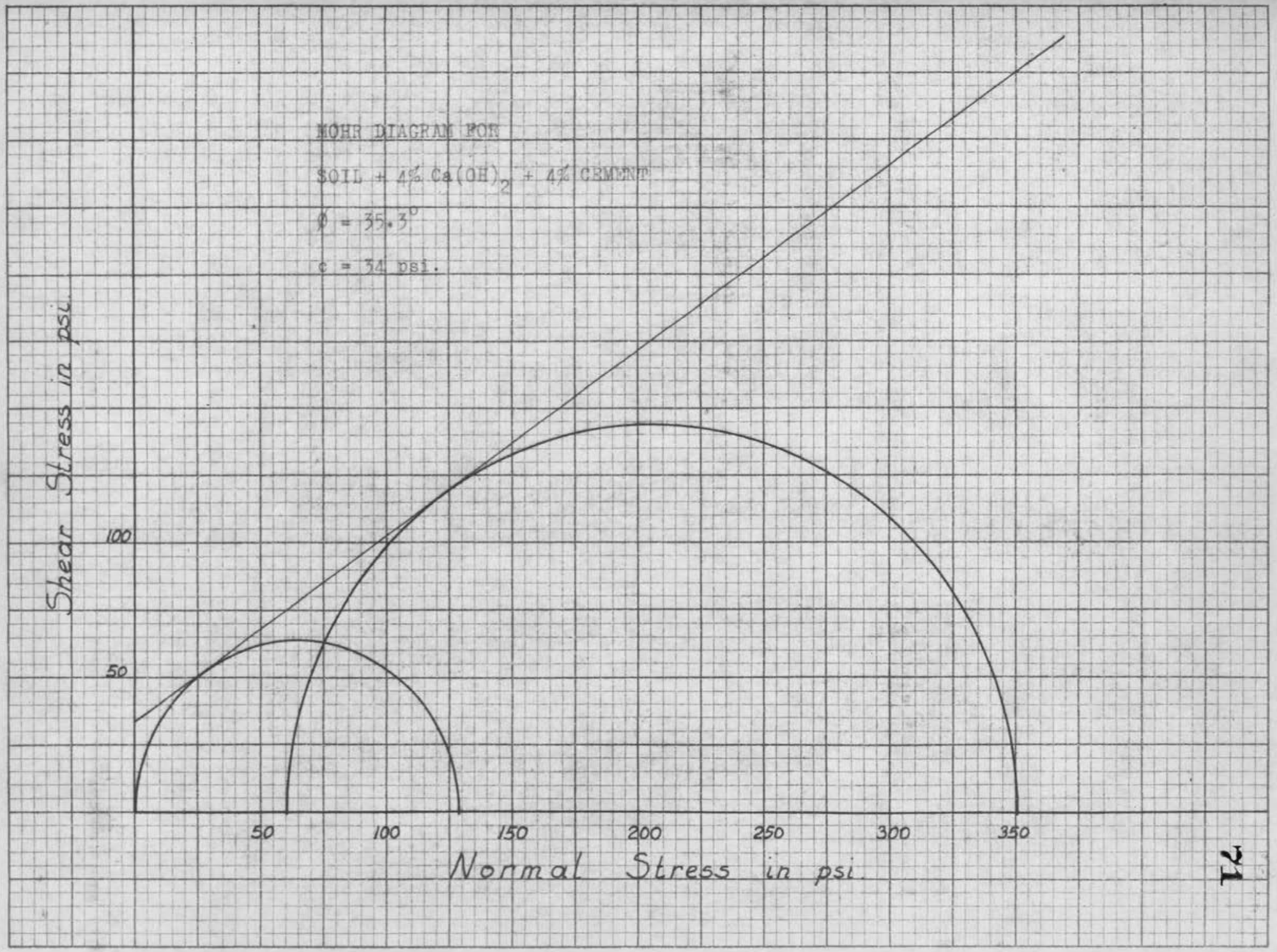

MOHR DIAGRAM FOR LEACHED
SOIL + 2% Ca(OH)2 + 6% CEMENT
ϕ = 32.6°
c = 32 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

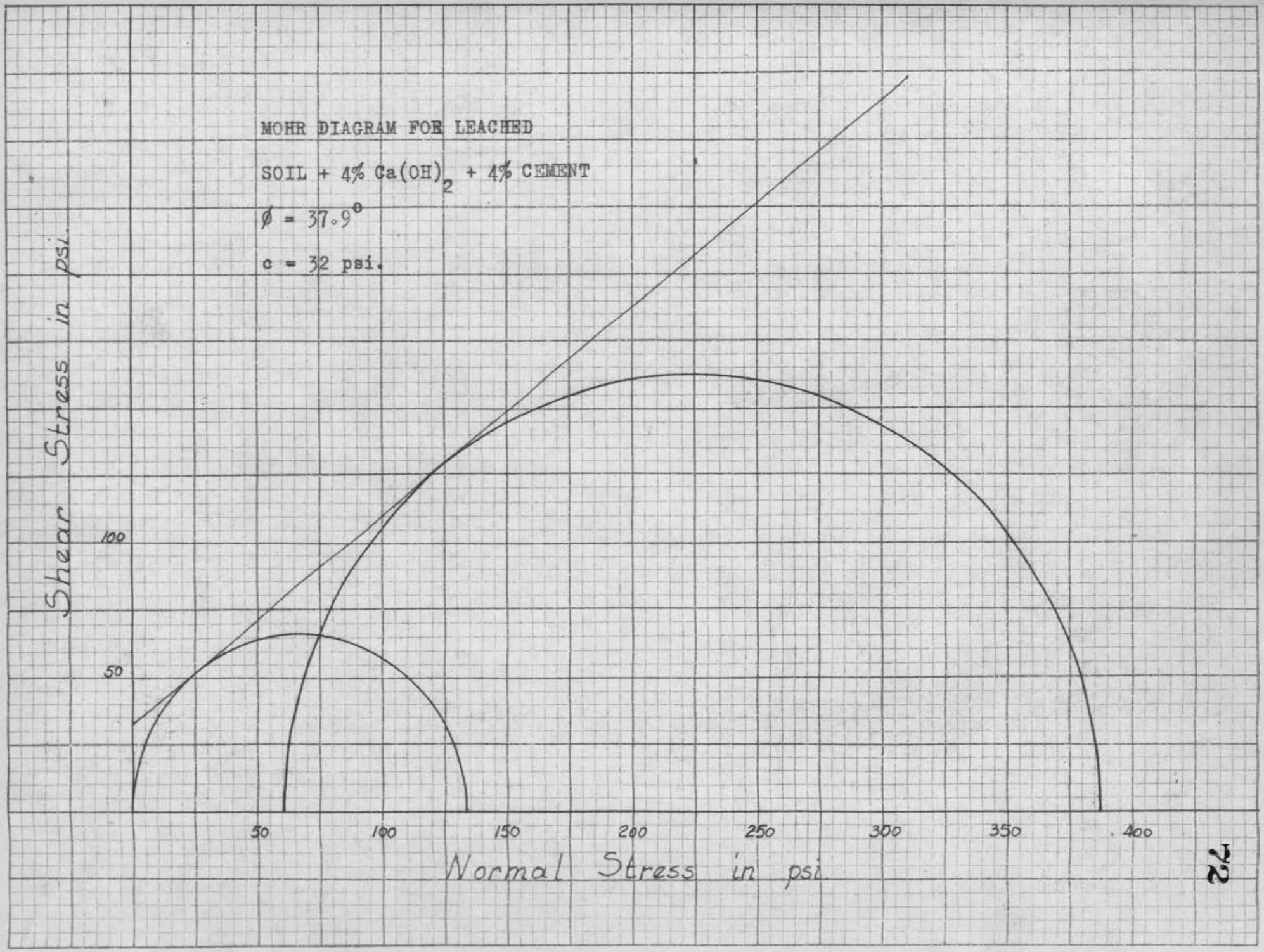

MOHR DIAGRAM FOR
SOIL + 4% Ca(OH)2
Ø = 30.5°
c = 23 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

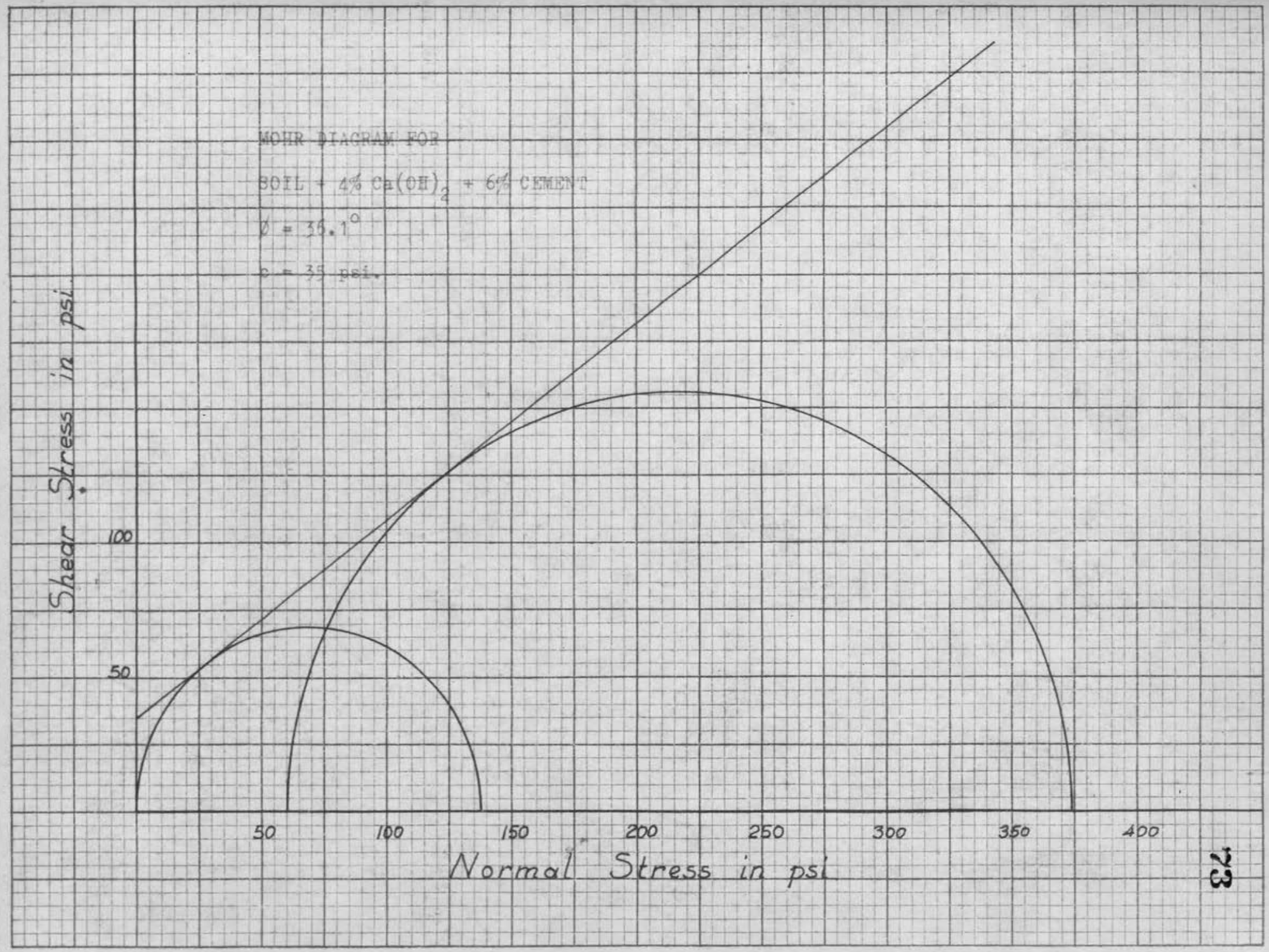

MOHR DIAGRAM FOR LEACHED
SOIL + 4% Ca(OH)2
Ø = 33.9°
c = 23 psi.
Shear Stress in psi
100
50
50
100
150
200
250
300
350
Normal Stress in psi

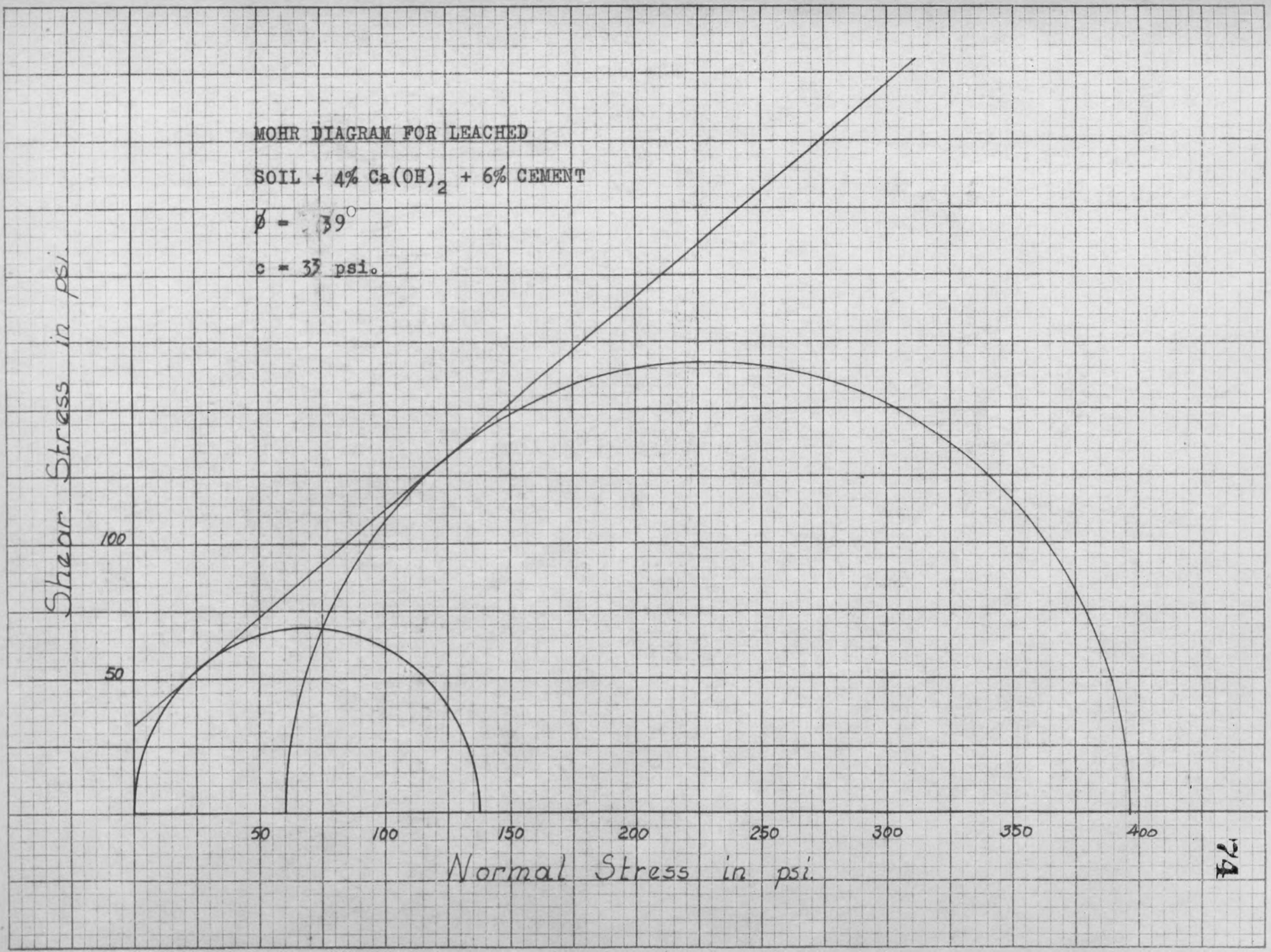

MOHR DIAGRAM FOR
SOIL + 4% Ca(OH)2 + 2% CEMENT
ϕ = 32.8°
c = 28 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

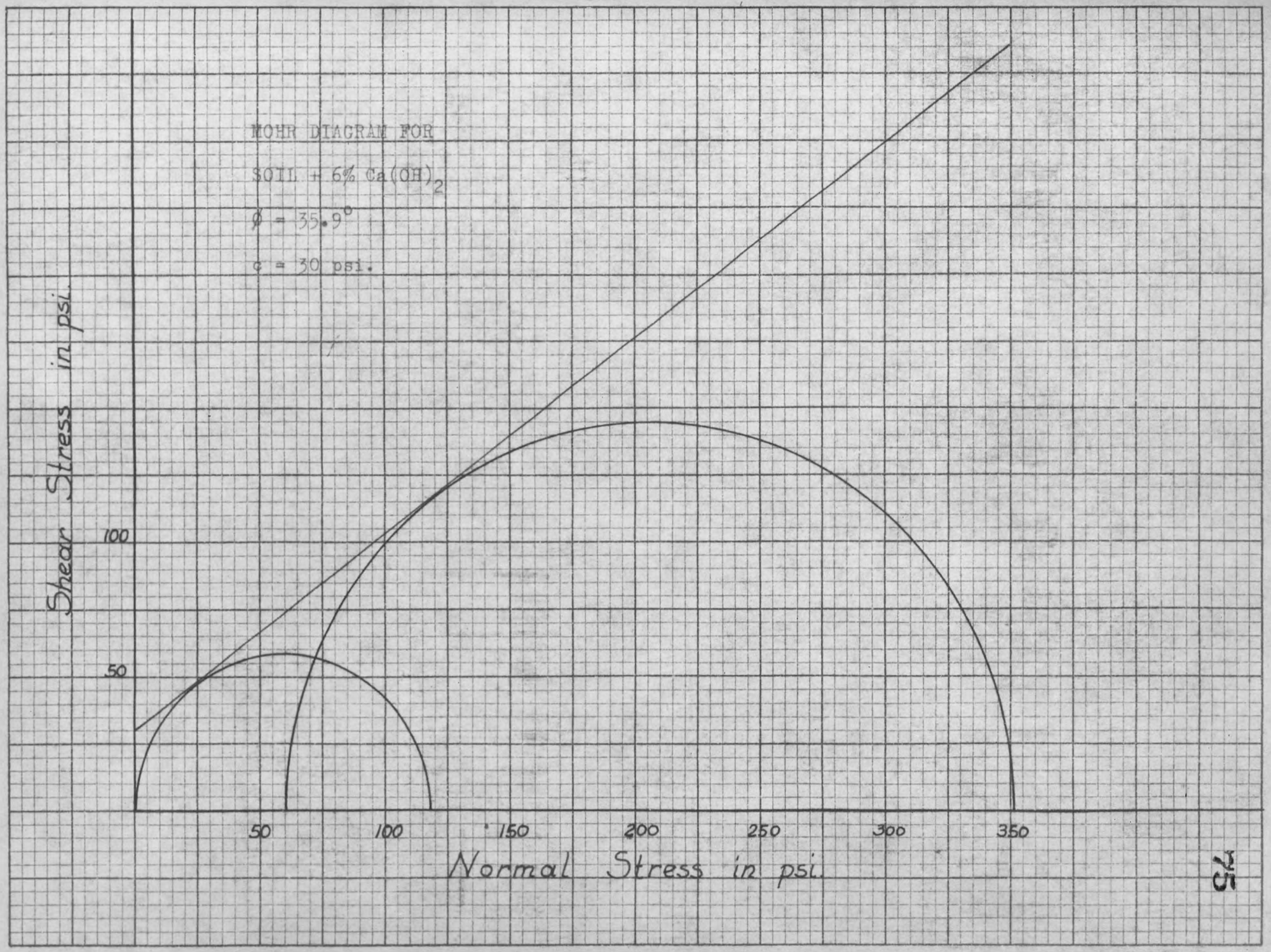

MOHR DIAGRAM FOR LEACHED
SOIL + 4% Ca(OH)2 + 2% CEMENT
ϕ = 35.8°
c = 26 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

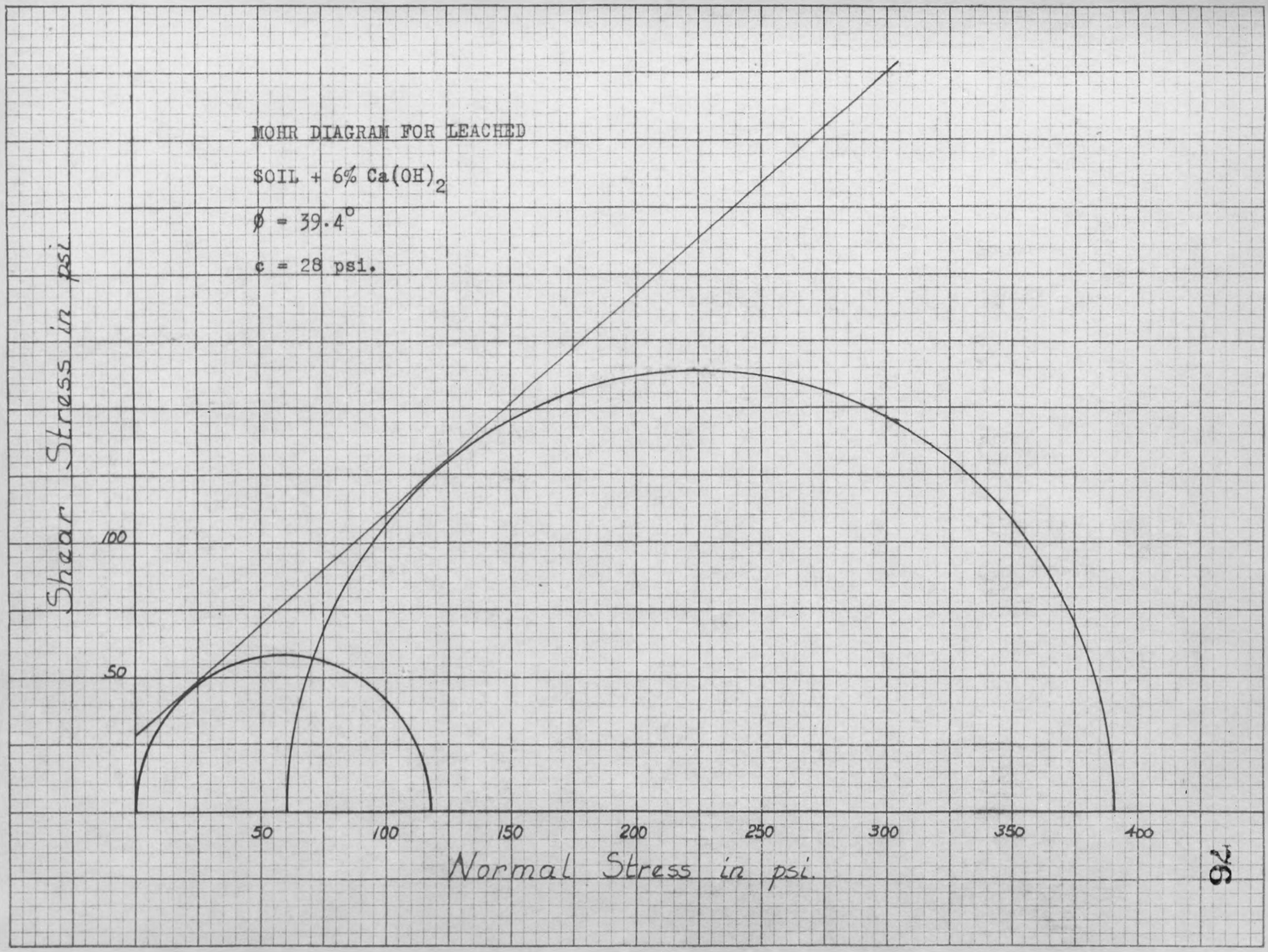

MOHR DIAGRAM FOR
SOIL + 4% Ca(OH)2 + 4% CEMENT
ϕ = 35.3°
c = 34 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

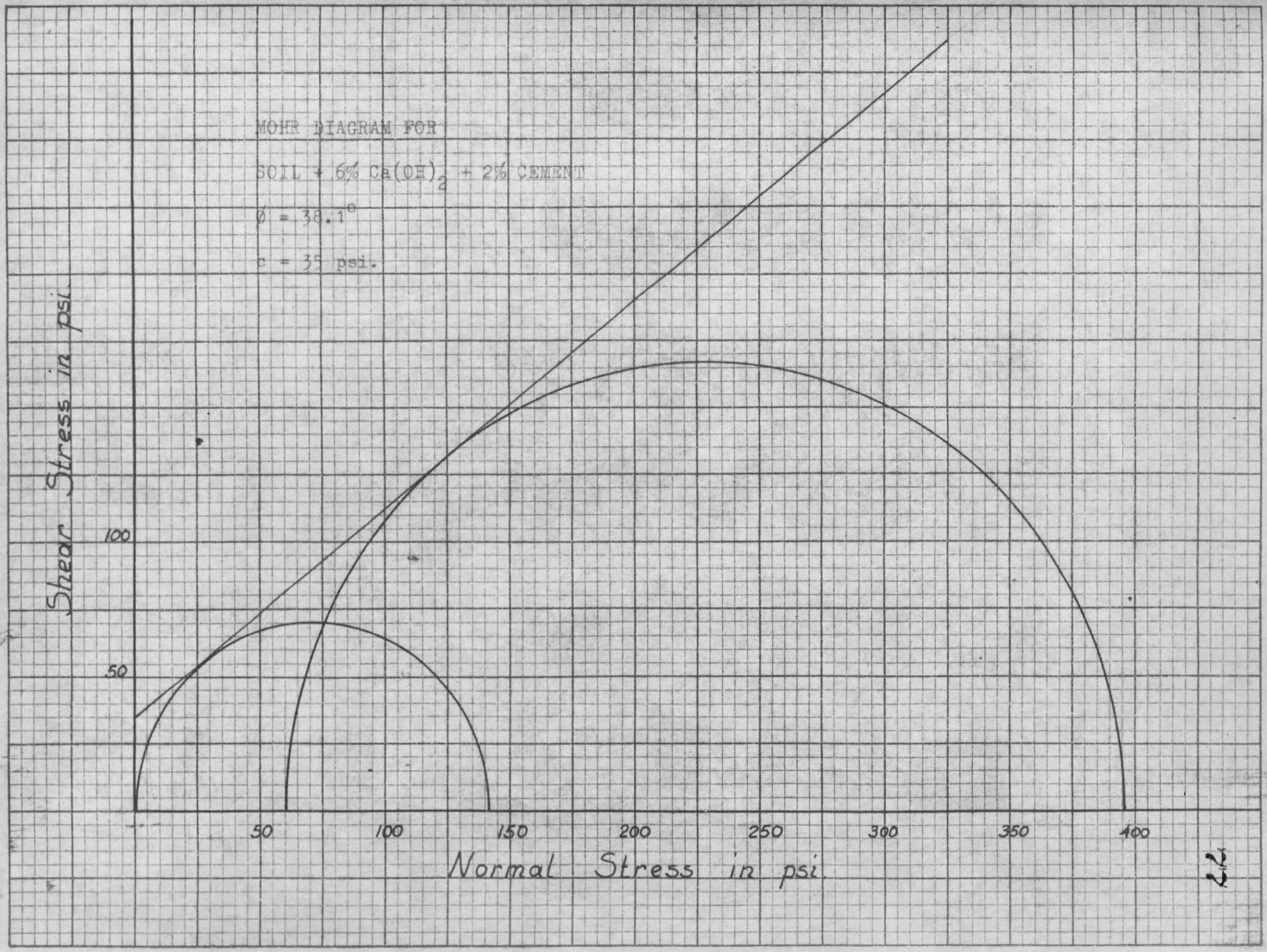

MOHR DIAGRAM FOR LEACHED
SOIL + 4% Ca(OH)2 + 4% CEMENT
ϕ = 37.9°
c = 32 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.

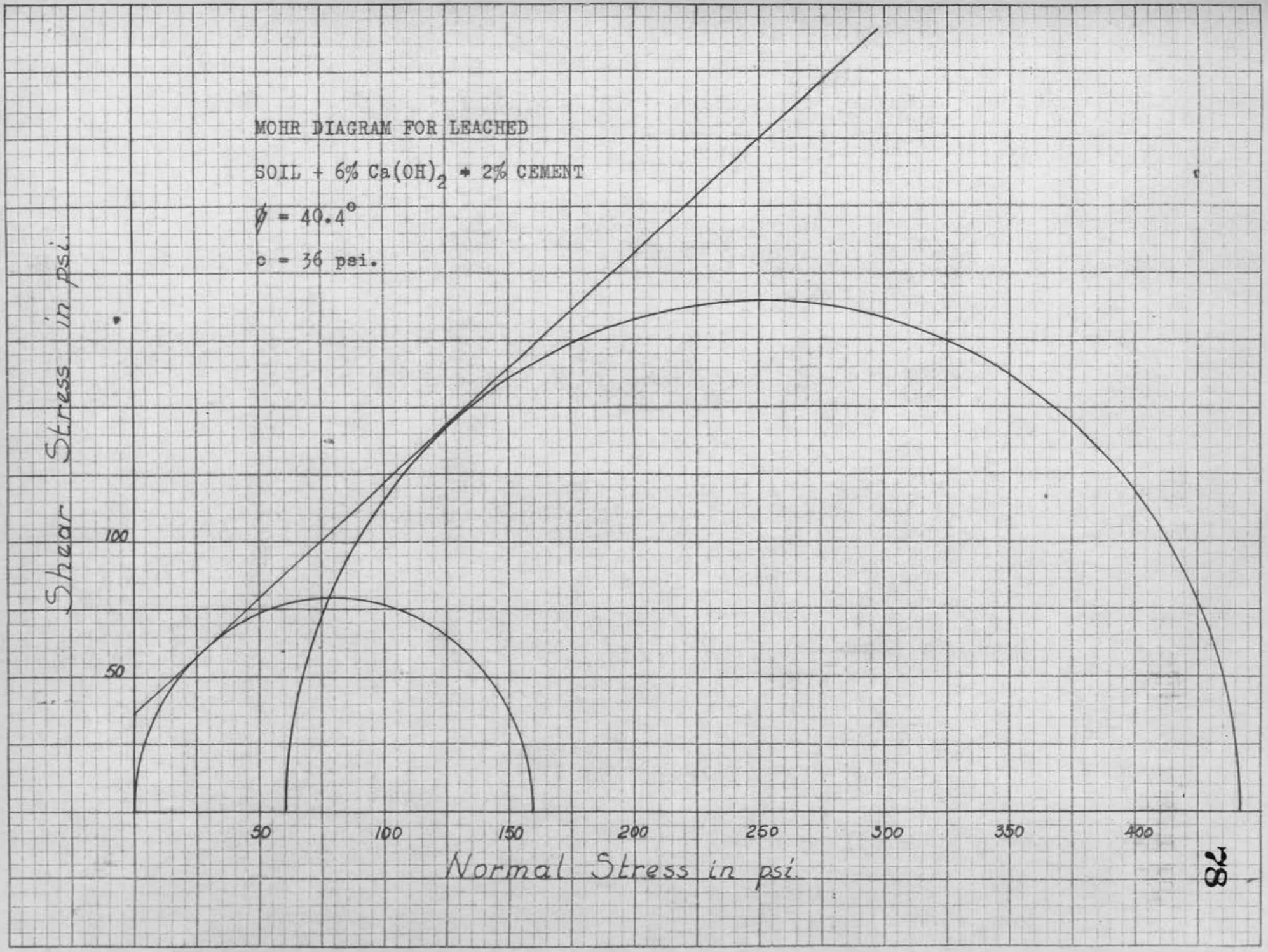

MOHR DIAGRAM FOR
SOIL + 4% Ca(OH)2 + 6% CEMENT
Ø = 35.1°
c = 35 psi.
Shear Stress in psi
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi

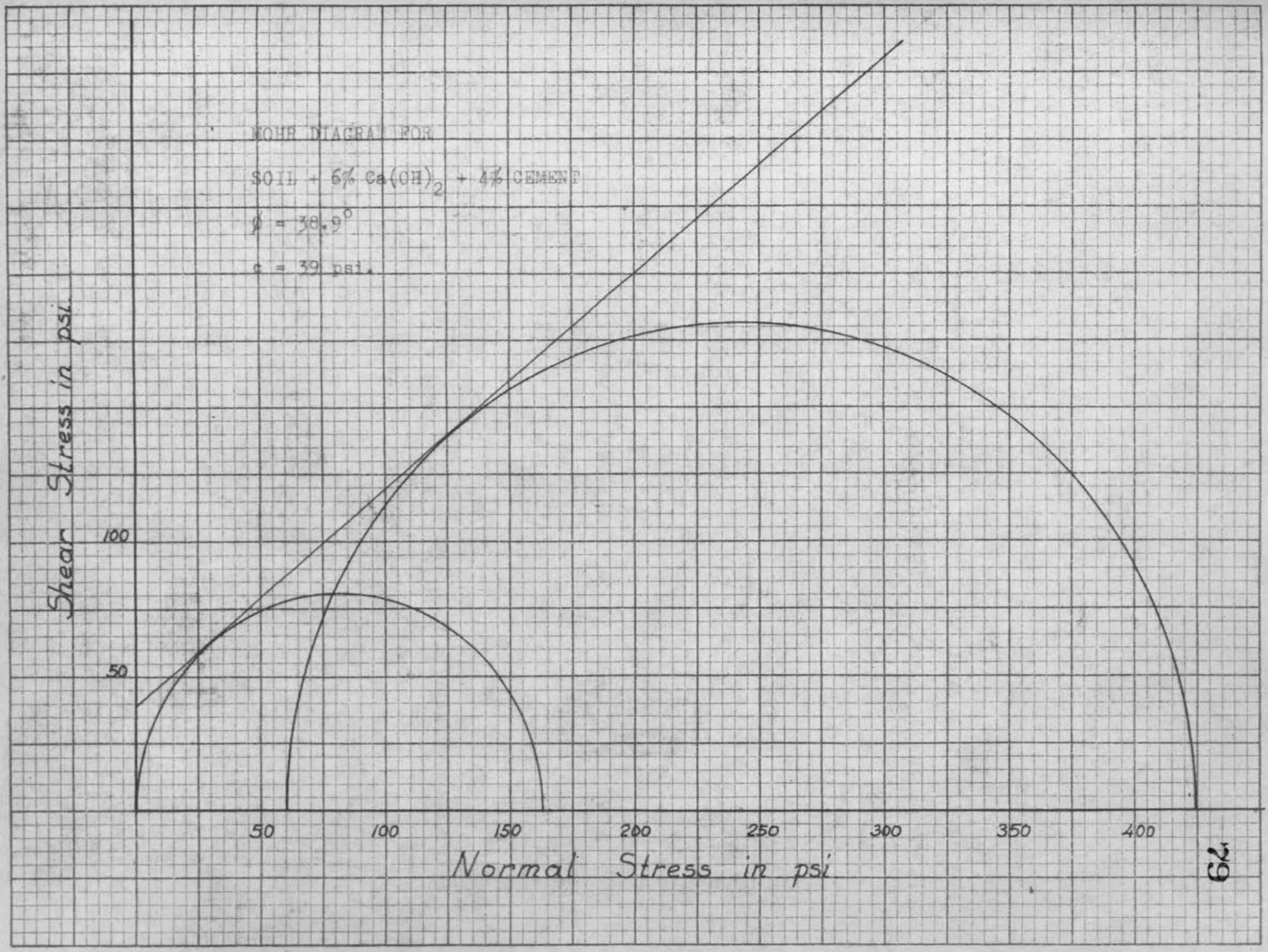

MOHR DIAGRAM FOR LEACHED
SOIL + 4% Ca(OH)2 + 6% CEMENT
ϕ = 39°
c = 33 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.

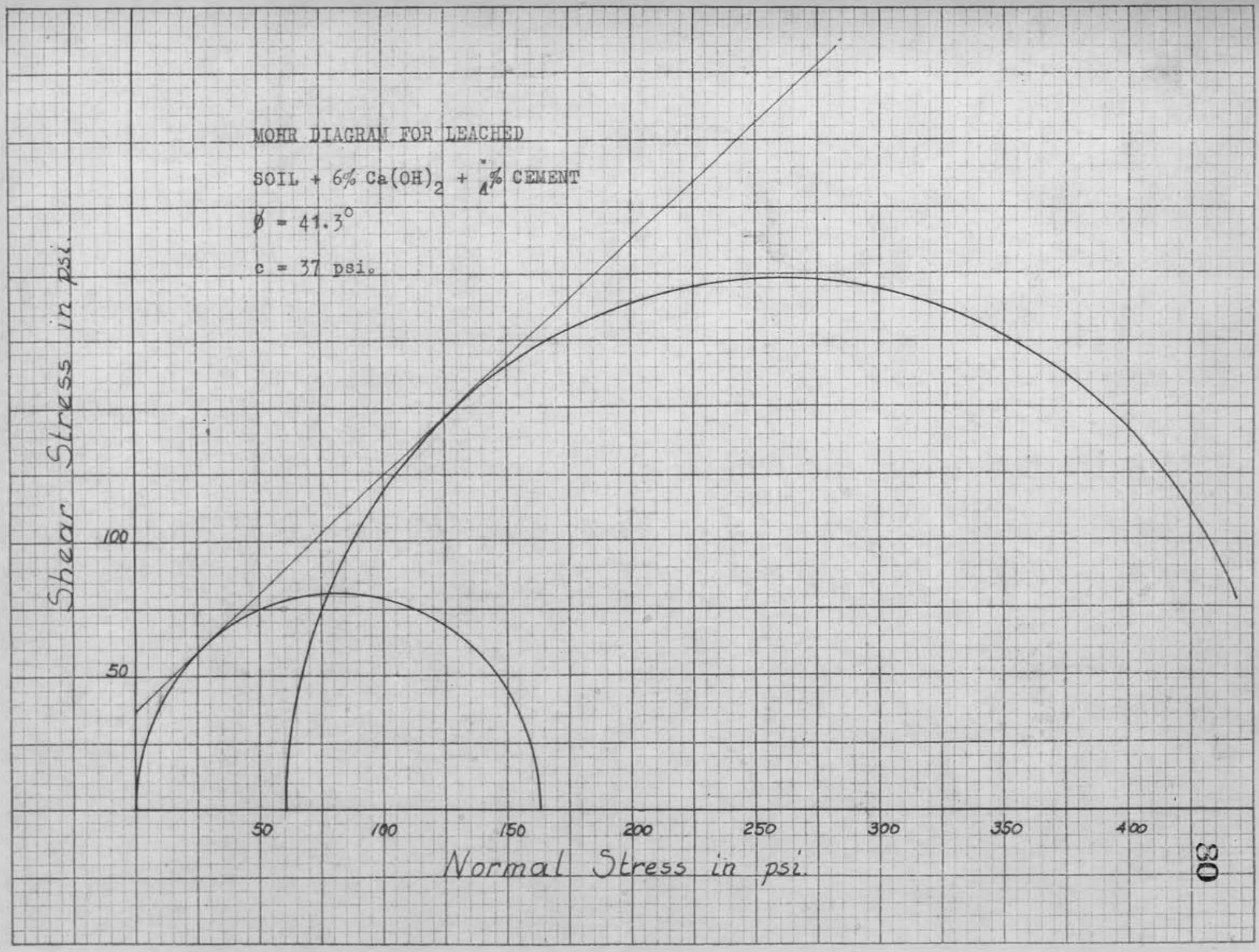

MOHR DIAGRAM FOR
SOIL + 6% Ca(OH)2
ϕ = 35.9°
c = 30 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
Normal Stress in psi.

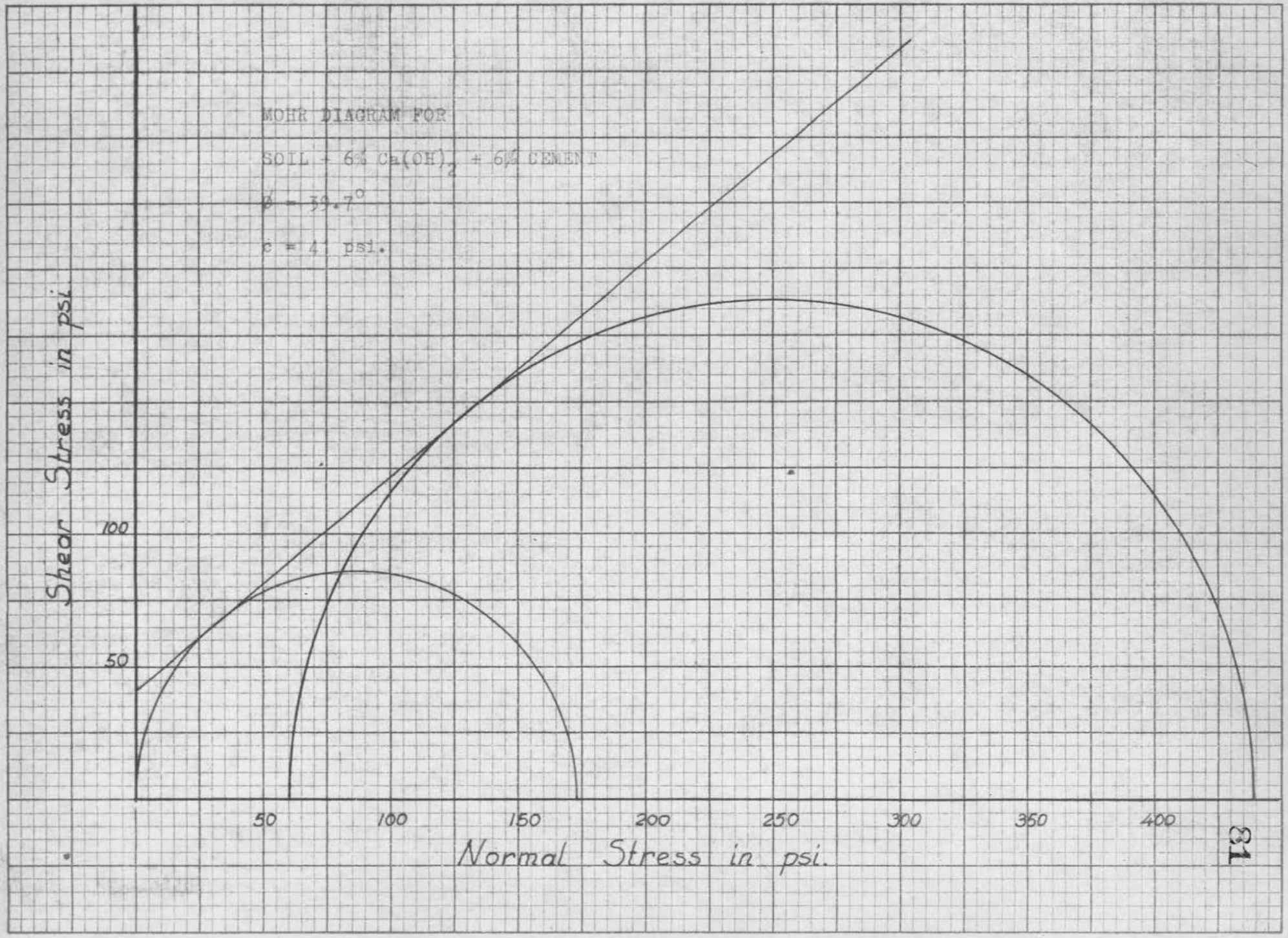

MOHR DIAGRAM FOR LEACHED
SOIL + 6% Ca(OH)2
ϕ = 39.4°
c = 28 psi.
Shear Stress in psi
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.

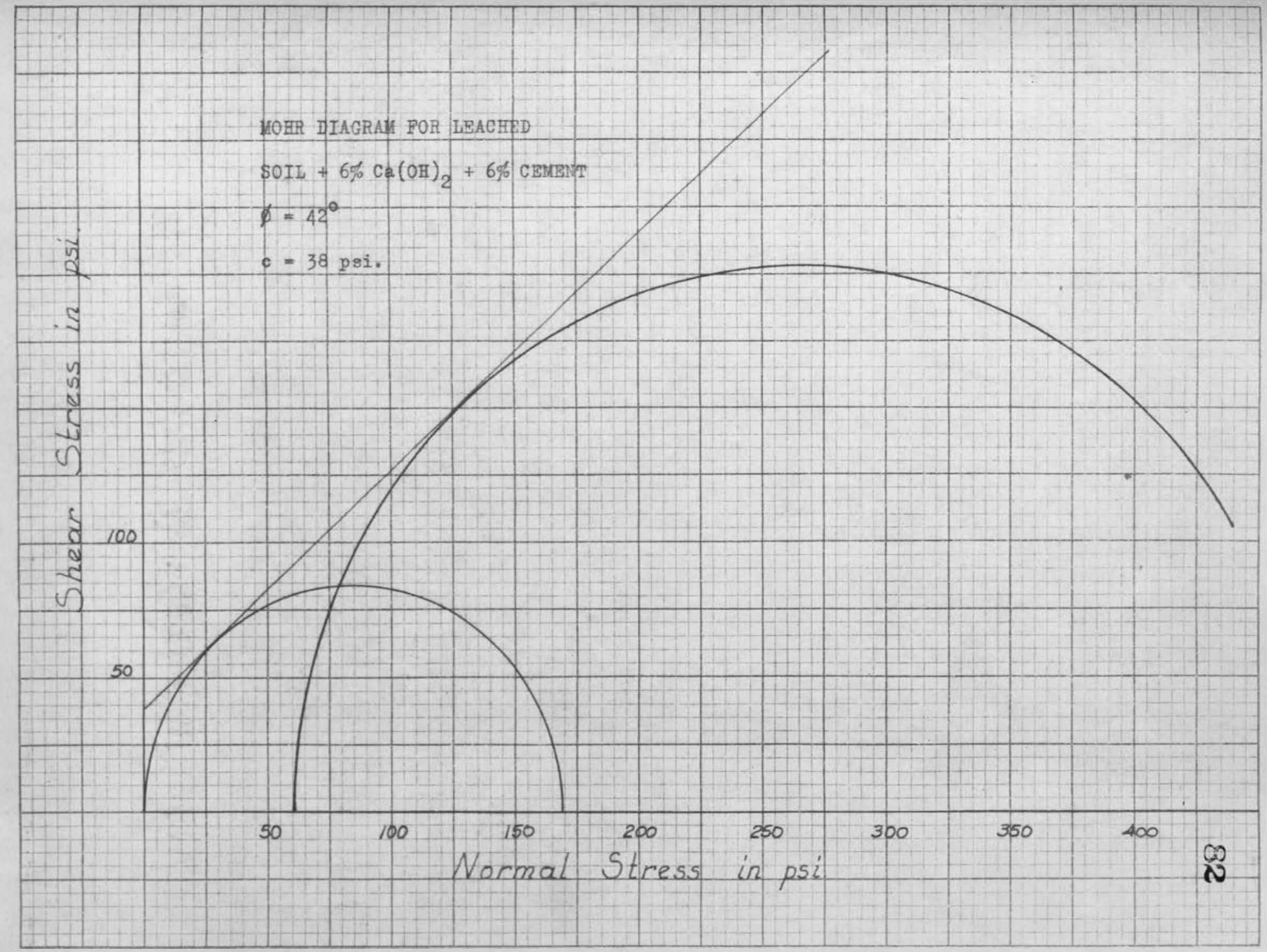

MOHR DIAGRAM FOR
SOIL + 6% Ca(OH)2 + 2% CEMENT
Ø = 38.1°
c = 35 psi.
Shear Stress in psi
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi


MOHR DIAGRAM FOR LEACHED
SOIL + 6% Ca(OH)2 + 2% CEMENT
ϕ = 40.4°
c = 36 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.


MOHR DIAGRAM FOR
SOIL + 6% Ca(OH)2 + 4% CEMENT
ϕ = 38.9°
c = 39 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi


MOHR DIAGRAM FOR LEACHED
SOIL + 6% Ca(OH)2 + 4% CEMENT
ϕ = 41.3°
c = 37 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.


MOHR DIAGRAM FOR
SOIL + 6% Ca(OH)2 + 6% CEMENT
ϕ = 39.7°
c = 41 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi.


MOHR DIAGRAM FOR LEACHED
SOIL + 6% Ca(OH)2 + 6% CEMENT
ϕ = 42°
c = 38 psi.
Shear Stress in psi.
100
50
50
100
150
200
250
300
350
400
Normal Stress in psi

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# VITA

Osman Yurdakul Ulugonul was born in Istanbul, Turkey on November 7, 1935. He attended elementary and high school in Istanbul, Turkey. In 1958 he received a B. S. Degree in Civil Engineering from I.T.U. Technical School and worked for an engineering construction company in Turkey for a period of one year.

In March 1959 he came to the United States on a graduate scholarship awarded by the Highway Department of Turkey based upon a competitive examination.

He attended language courses at Queens College, New York City for seven months and then enrolled for graduate work at the Missouri School of Mines and Metallurgy in September, 1959.

He is a member of Chi Epsilon, National Civil Engineering Honor Fraternity and the American Society of Photogrammetry. He will receive his M. S. Degree in Civil Engineering from the Missouri School of Mines and Metallurgy in January, 1961.